I. C. 6663

NOVEMBER, 1932

DEPARTMENT OF COMMERCE

UNITED STATES BUREAU OF MINES
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INFORMATION CIRCULAR

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BY

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By G. E. McElroy[2]

INTRODUCTION

The purpose of this paper is not to present new data on the pressure losses due to bends and changes of area in mine openings through which air flows, but rather to correlate existing data, determined mainly on small duct systems and expressed in a variety of ways, according to uniform methods that facilitate their use in pressure-loss computations. These are required in such air-flow problems as determining the quantity that will flow through mine openings under a certain pressure difference or, conversely, the pressure difference that will be required to maintain a certain rate of flow.

Air flowing through ducts, such as mine airways, encounters resistance to flow due to interference of the individual air streams with each other caused by the wall surfaces. The result is that part of the kinetic energy of the flowing stream is converted to heat; and constant renewal of the kinetic energy from the total energy of the flow is required to maintain it. This process manifests itself by a decrease of the total pressure (static pressure plus velocity pressure) of the air in the direction of flow; in order that flow may occur, there must necessarily be a difference in total pressure between the two ends of the airway equivalent to the pressure losses occasioned by the flow, which automatically adjusts itself in magnitude to the pressure difference maintained.

Pressure losses may be divided into two separate types, according to their mode of origin: "Friction" pressure losses caused by the drag of the walls on the air stream, which are dependent primarily on the condition of roughness of the individual wall surfaces; and "shock" pressure losses caused by changes in the area occupied by the air stream as affected by either deflection from a straight line or by changes of area of the airway, which are dependent primarily on the relative positions of the individual wall surfaces with respect to the lines of flow.

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[1] The Bureau of Mines will welcome reprinting of this paper, provided the following footnote acknowledgment is used: "Reprinted from U. S. Bureau of Mines Information Circular 6663."

[2] Mining engineer, U. S. Bureau of Mines.

SHOCK PRESSURE LOSSES

All departures from the condition of straight airway of uniform cross-sectional area result in pressure losses that are here termed "shock" pressure losses. This expression has heretofore had a more limited application, having been reserved for designating the pressure losses accompanying abrupt enlargement of the airway in the direction of flow and due to a faster stream expanding into a larger area and slower stream. The term has been selected for broader application because analyses of experimental results indicate that it designates the mode of action for all pressure losses other than friction losses; that is, they are due in all cases to shock loss resulting from a faster stream expanding into a slower stream. Although all shock losses may be considered as caused by changes in the area actually occupied by the flow, it is convenient to divide them into two general classes: Those caused by changes in direction of the airway, and those caused by changes of area of cross section of the airway.

General Formula for Shock Pressure Losses

Shock pressure losses have been found to bear a constant ratio to the velocity pressure corresponding to the mean velocity of flow - absolutely constant in the case of most conditions of area changes, and practically constant in the case of bends. They can be generally represented and computed, therefore, by means of the general formula,

$$H = X H_v \qquad (1)$$

where H is total shock pressure loss in inches of water,
H_v is the velocity pressure corresponding to the mean velocity of flow, in inches of water,
and X is an empirical factor based on experiments and termed the "shock factor."

Since H and H_v are always expressed in the same units and are equally affected by air density changes, X is independent of both density and the unit used, in which respect it differs from the friction factor used in formulas fo computing friction losses. It is the number of velocity pressures equivalent to the shock pressure loss. When it is desired to make a summation of individual shock losses that occur regularly along an airway, it is the number per unit of length, for which 100 feet will be used throughout this paper.

SUMMARY OF DATA AVAILABLE ON SHOCK FACTORS

The object of this paper is, therefore, to present the results of an examination and analysis of existing data on shock pressure losses at bends a area changes in terms of shock factors for application to mine airway conditions.

The examination reveals that, although we have no rational method of computing shock factors for bends, we do have a large number of direct determinations of factors for bends in ducts of uniform area for which the general relations are sufficiently consistent to permit their general application to bends in mine airways of uniform area. The magnitudes of the shock factors given by different sets of test data are so inconsistent, however, due to abnormal flow conditions in test installations, that their application to normal flow conditions in mine airways is subject to a large degree of approximation. No rational method of computing factors for bends in airways of nonuniform areas is available and but few directly determined factors. Unsymmetrical expansion is involved, for which we have no law, and the effect of nonuniform areas on the degree of contraction that takes place in the flow is also unknown. Bends between sections of different areas are a very common condition in mine airway systems, but we can not compute factors for them with any degree of certainty until more data are available.

For symmetrical area changes in mine airways, we not only have a rational method of computing shock factors for practically all of the conditions encountered, but also very good agreement in the data required for the computations. However, area changes in mine airways are rarely symmentrical and, as in the case of bends between different areas, we have no rational method of computing the shock factors for nonsymmetrical area changes and we have only a few directly determined shock factors for such conditions. Unsymmetrical expansion is also involved in this case, and the effect of lack of symmetry on contraction factors is also unknown. We can not compute shock factors for unsymmetrical area changes in mine airways with any degree of certainty, therefore, until more data are available.

Apparently, the standard formula for shock loss applies only to conditions of symmetrical expansion around the whole perimeter of the air stream and does not apply to conditions of unsymmetrical expansion, although it has always been assumed to hold for unsymmetrical conditions without, to the author's knowledge, any theory or test results to confirm the assumption. Until we have a verified formula for computing shock losses due to unsymmetrical expansion, we will have to be satisfied with direct determinations of shock factors limited in application to the exact conditions of the test installation. It is possible that a few comparatively simple tests would reveal the desired law, or that it may be deduced from available test results; also, it appears probable that it will be found to be connected to the law for shock loss for symmetrical expansion through some simple function of the proportional part of the perimeter involved in the unsymmetrical expansion and that contraction coefficients will also be found to be similarly related.

Shock Factors in Terms of Friction Factors and Equivalent Lengths

Friction pressure losses are of major importance in almost any air-flow system; the common disposition, therefore, has been to compute the shock losses with the friction losses by means of various conventions of a greater or less degree of approximateness. This procedure may be justified for duct systems in which the shock losses are relatively unimportant and the wall conditions are very uniform, but a more exact procedure is desirable for mine airway systems in which the shock losses are relatively important and the wall conditions are rarely uniform.

Shock losses have been found to be dependent on the relative positions of the wall surfaces and independent of the degree of roughness of the surfaces. For this reason they can not be computed correctly as friction pressure losses, although methods for obtaining approximate accuracy over a limited range of conditions are available.

Many of the data available on shock losses are expressed in terms designed to facilitate their computation as friction losses - that is, as increments to the friction factor or as equivalent lengths of airway expressed in feet or diameters.

It is therefore desirable to develop the formulas required for obtaining shock factors for shock pressure losses expressed in these forms.

A standard formula for computing friction pressure losses is

$$H_f = \frac{K\ P\ L\ V^2\ d}{5.2\ A\ \ 0.075} \qquad (2)$$

where H_f is total friction pressure loss, in inches of water,
K is an empirical factor for air having a density of 0.075 pound per cubic foot and termed the "friction factor,"
P is perimeter of cross section in feet,
L is length in feet,
V is mean velocity of flow in feet per minute,
d is weight of air in pounds per cubic foot,
and A is area of cross section in square feet.

A standard formula for computing velocity pressure is

$$H_v = 0.0^6831\ V^2\ d \qquad (3)$$

where H_v, V, and d have the same designations as before.

Increments to Friction Factor.- Shock losses that are regularly intermitt are computed along with the friction losses by increasing the friction factor used enough to make the result of the computation cover the total of both type of pressure losses.

If K' denotes the friction factor estimated so as to include a shock pressure loss of X velocity pressures imposed upon each 100 feet of an airway for which the strictly friction pressure loss is that corresponding to a friction factor K, then K' = K + k, where k is the increment to the normal friction factor required for including the shock pressure loss. By transposing (2) and expressing velocity in terms of velocity pressure from (3), we have, for the increment to K at standard air density conditions of 0.075 pound per cubic foot,

$$k = \frac{X\ H_v\ 5.2\ A\ 0.075}{L\ P\ V^2\ d} = \frac{X\ H_v\ 5.2\ A\ 0.075}{100\ P\ d\ \dfrac{H_v}{0.0^5 831\ d}} = 0.0^8 324\ \frac{A}{P}\ X \qquad (4)$$

The increments to K thus vary directly as the $\frac{\text{area}}{\text{perimeter}}$ ratio and, since this ratio is largely a matter of the actual size of the airway, the variation in increments for constant values of X per 100 feet is large. For a 6-inch circle or square the A/P ratio is 0.125, for a 6-foot circle or square it is 1.5, and for a 20-foot circle or square it is 5.0. However, the A/P ratios for mine airways of the sizes normally encountered range only from about 1.0 to 2.0, with an average of approximately 1.5, for which the increment to the friction factor is about $0.0^8 5$ times X per 100 feet of airway. Compared to the normal friction factors, the increments are relatively small for rough-walled mine airways and the values of X available offer but an approximate degree of selection, so that the possible accuracy of results of calculations is little affected by this method of computing shock losses if it is limited to the ordinary range of sizes of mine airways. For more accurate results, and for airways or ducts that do not fall within this area range, the shock losses should be separately computed, or, if computed by use of the friction loss formula, the increments to the normal values of K should correspond to the actual A/P ratios.

Equivalent Length in Feet.- In computing the total pressure loss by means of the friction formula shock losses that are strictly local are allowed for by arbitrarily increasing the length over the actual length a sufficient amount to make the result agree with the total of both types of pressure loss. The increment in length required is often given in terms of the equivalent number of diameters rather than directly in feet.

The expression of shock losses in terms of equivalent feet of airway requires that the actual length of airway be increased by a length, L, that would have a friction loss equivalent to the shock loss XH_v, the length used for computation in the friction loss formula being the actual length plus L. By transposing the friction formula and expressing velocity in terms of velocity pressure, we have, for the increment L at standard air density,

$$L = \frac{X\ H_v\ 5.2\ A\ 0.075}{K\ P\ V^2\ d} = \frac{X\ H_v\ 5.2\ A\ 0.075}{K\ P\ d\ \dfrac{H_v}{0.0^6 831\ d}} = 0.0^6 324\ \frac{A}{K\ P}\ X \qquad (5)$$

Since the equivalent length in feet varies both directly as the $\frac{\text{area}}{\text{perimeter}}$ ratio and inversely as the friction factor, the range of increments for constant values of X is so large that approximate accuracy of direct application of test data is possible only for a very limited range of values of K and A/P. For the limited range of average mine airway conditions, the equivalent length in feet varies from about 300 X to 15 X.

Equivalent Length in Diameters.- The expression of shock losses in terms of equivalent diameters of airway or duct merely means that the increment of length, L, is divided by the diameter, D. The ratio A/P can also be expressed in terms of the diameter, D, thus:

$$\frac{A}{P} = \frac{\frac{\pi D^2}{4}}{\pi D} = \frac{D}{4} \qquad (6)$$

Dividing (5) through by D and substituting D/4 for A/P, we have,

$$\text{Equivalent diam.} = \frac{L}{D} = \frac{0.0^{6}324\ \frac{A}{K\,P}\ X}{D} = \frac{0.0^{6}324\ \frac{D}{K\,4}\ X}{D} = \frac{0.0^{7}81}{K}\ X \qquad (7)$$

The equivalent number of diameters is thus independent of the A/P ratio and for constant shock factors, varies inversely as the friction factor. The range of direct application of test data is therefore limited only to corresponding degrees of roughness of airway, or duct. Such an expression of shock losses is therefore useful in those fields of ventilation where ducts of approximately uniform conditions of roughness are the only airways involved, but it is not applicable to mine ventilation conditions of very variable conditions of roughness, as expressed by friction factors ranging from $0.0^{8}20$ to $0.0^{7}20$ for conditions commonly encountered, and for which the equivalent diameters may vary fro about 40 X to 4 X.

Conversion Chart.- A graphic chart for converting shock factors to equivalent increments to friction factor or length, or vice versa, is presented in Figure 1. Slide-rule computations, based on formulas (4), (5), and (7) are the most simple and rapid means of converting factors, but the chart offers a rapi independent check of results.

The chart appears complex because three charts have been combined into one but it is easily used, offering simply a graphic method of performing the multiplications and divisions designated by the three formulas, with the scales of values arranged to correspond. The solutions of three examples - the conversion of X to k, L and $\frac{L}{D}$ for a particular set of conditions - are shown on the chart by dotted lines, with arrows to show the methods of procedure. These are also shown by the three thumb-nail sketches in the lower right-hand corner of the chart. Although separate scales of A (area) and P (perimeter) are provided for the graphic determination of the $\frac{A}{P}$ ratio, the latter appears as a separate scale which can be used directly with approximate accuracy by means of the parallel scale of equivalent D's, or size of equivalent circles or squares.

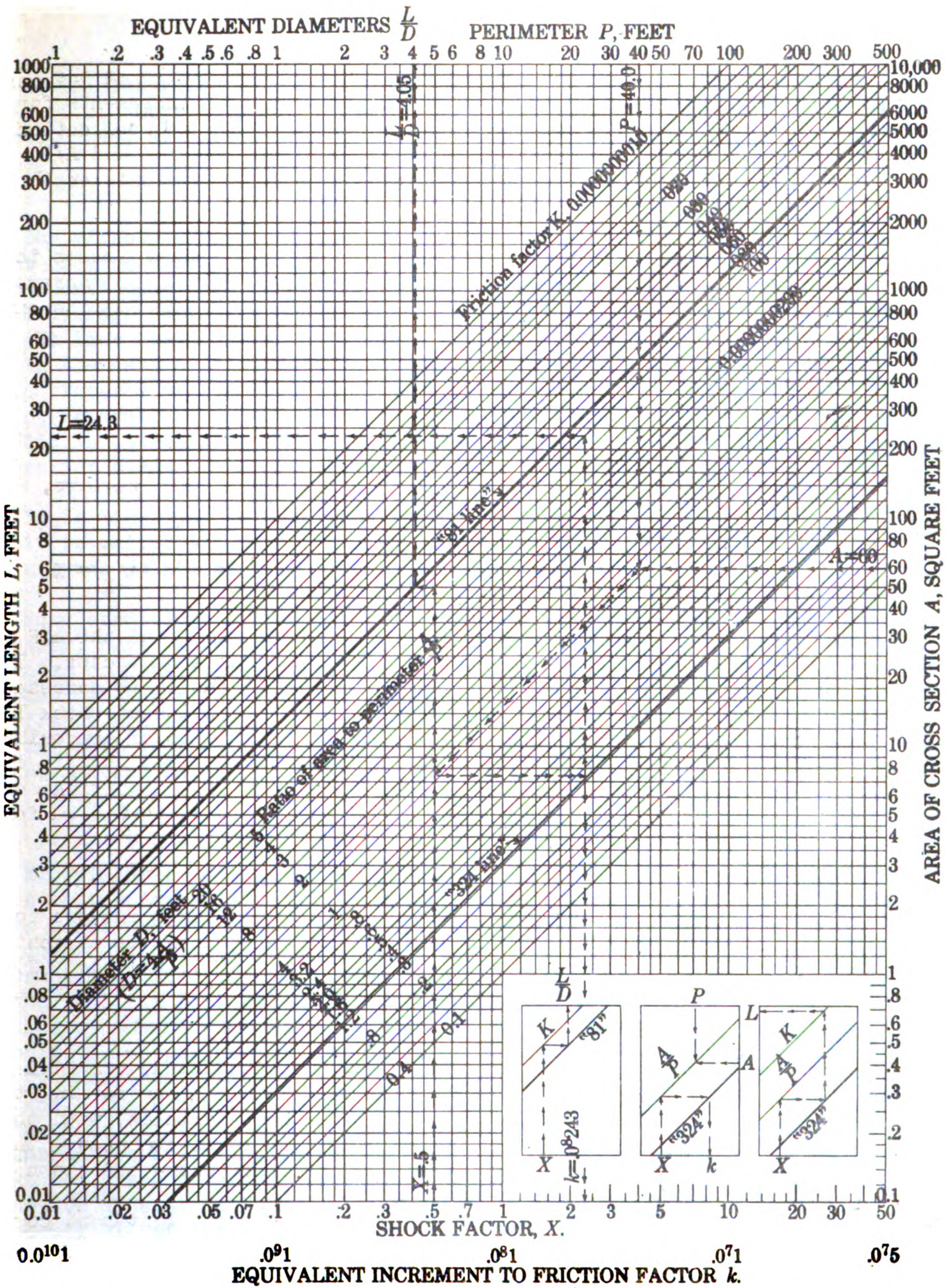

Figure 1.- Chart for determining corresponding values of shock pressure losses expressed in terms of shock factors, increments to friction factors, or equivalent lengths in feet or diameters

In the examples solved $A = 60$ square feet, $P = 40$ feet, $K = 0.0^{7}1$ and $X = 0.5$. Corresponding values of k, L and L/D are determined from the chart to be $0.0^{8}243$, 24.3 feet, and 4.05 diameters respectively.

Shock Factors for Bends

The effects of deflections from a straight line are important in their effect on mine airway pressure losses, since absolutely straight airways, except in the particular case of shafts, are the exception rather than the rule. The normal average variation of the exact center of successive sections from the straight line averaging such points - that is, the average irregularity (alignment in the case of timber-lined airways) of so-called "straight" sections - should properly be included in this class of losses, but the effects are small and not separable from the friction pressure losses with which they are always included in determining the range between minimum and maximum values of friction factors for clean, straight airways.

It is important to note that the angle of a bend is the angle through which the air is deflected - that is, 180° minus the angle as commonly designated; thus airways joined at a 135° angle produce a 45° bend.

Many conditions of the air flow, such as velocity, area, density and viscosity, which have been found to affect the constancy of friction factors to a greater or less degree dependent on the range of conditions considered, have somewhat similar effects on the constancy of shock factors for bend losses, but the effects are so small, in comparison with the uncertainty of application of existing data to the irregular conditions presented by mine airways, that they will be ignored here.

Flow Conditions at Bends

Experimental determinations of shock losses at bends indicate that the air crowds to the far side of the bend and occupies less than the full area available at the departure end of the bend; and that the excess of pressure loss, over that due to friction as determined by the rubbing surface, is a shock loss due to abrupt one-sided expansion from this contracted area to the full area following the bend, as pictured in Figure 2. The degree of contraction in the area occupied by the flow at the departure end of the bend is apparently determined not only by the position of the walls of the airway throughout the bend, but also by the distribution of velocities over the cross section at entrance to the bend. The expansion is made at a small angle and thus takes place over a considerable length of airway downstream of the bend, depending on the degree of contraction preceding the expansion; and throughout this section not only are static pressure measurements unreliable, but the average velocity pressure can not be determined from area and quantity data, since the air stream does not occupy all of the cross section of the airway. Where expansion takes place from the contracted stream direct to the atmosphere, as from an elbow on the end of a duct, the shock loss is much larger than that for abrupt expansion to the airway area only on account of the greater difference in the velocities involved. The ratio of the shock losses for these two conditions of installation of the same bends is reported to be practically constant regardless of the type of bend; various sets of tests give figures (not corrected for included friction losses) ranging from 56 to 67 per cent for the loss with following duct in terms of the loss without following duct. This difference of shock pressure losses for the two different conditions of installation is often explained as due to "conversion" of pressure following the bend, whereas it results only because of the difference in conditions of shock loss.

The abrupt expansion in the area occupied by confined flow following a bend is not symmetrical but one-sided, or at least affects but part of the perimeter of the section, and the standard formula for shock loss - as equal to the velocity pressure corresponding to the difference of the velocities involve - apparently does not apply. However, it is a simple matter to determine the shock loss directly by test and express it in terms of velocity pressures, or shock factors.

In mine airways, the area following the bend is rarely the same as the area preceding the bend, a condition that affects the degree of contraction an the shock loss. In order to calculate the shock losses for such conditions it is needful to know not only the effect of nonuniform area conditions on the co traction coefficient, or ratio of contracted area to area at entrance, but also a formula for the shock loss due to unsymmetrical expansion. Until we have these data, the calculation of pressure losses for bends in airways of nonuniform area must be approximate at best. With few exceptions, therefore, our data on shock factors for bends are limited to conditions of uniform area of cross section.

Sinuosity, Crookedness, and Curvature

Mine airways often include numerous small bends and curves, involving deflections of 30° or less, and are termed "sinuous," "crooked," or "curved," as the case may be. Drifts following a vein and alternately turning one way and then the other may be "sinuous" if largely composed of short curved sections or "crooked" if of short straight sections. Where the deflections are approximately constant and in the same direction, there are "continuous curves" or "turns." The conditions are usually very irregular and the individual shock pressure losses are so small as to defy calculation, but a very rough approximation may be made of the combined shock losses from existing data[3], as follow

> Slight degree; $X = 0.2$ per 100 feet. A large-radius curve, a sharp bend of about 15° deflection, or a wall-line close to the center line, where they occur separately and not oftener than once every 100 feet; or a small-radius curve, a sharp bend of about 30° deflection, or a wall-line crossing the center line, where they occur separately and not oftener than once every 200 feet.

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[3] McElroy, G. E., and Richardson, A. S., Resistance of Metal-Mine Airways: Bull. 261, Bureau of Mines, 1927, p. 131.

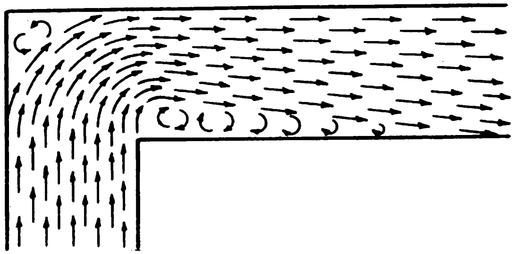

Figure 2.- Sketch showing general conditions of flow at bends in airways

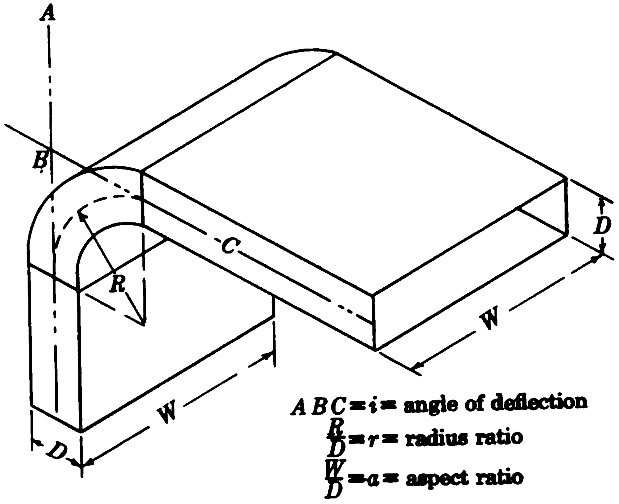

Figure 3.- Sketch defining bend characteristics

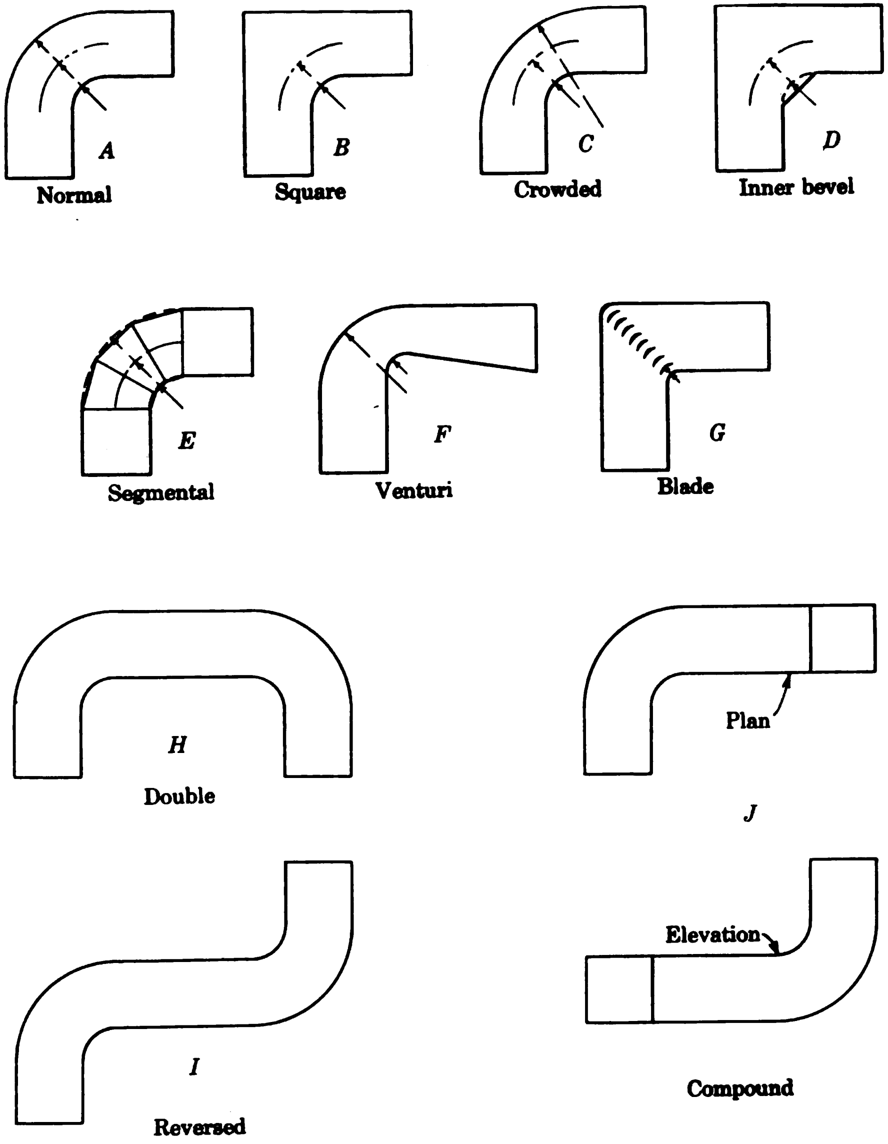

Figure 4.- Common types of right-angle bends

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Moderate degree; $X = 0.3$ per 100 feet. Conditions intermediate between slight and high degree.

High degree; $X = 0.5$ per 100 feet. A continuous large-radius curve, a continuous turn of repeated small deflections of 10° to 15° every 20 to 30 feet, bends of 20° to 30° deflection every 50 to 100 feet, or a wall-line crossing the center line about every 50 feet.

The foregoing descriptions are rather meager for lack of comprehensive test data, but they are sufficient to permit of approximate computations for mine airways, which is about all that the variable area conditions of such airways usually justify.

Single Right-Angle Bends

Deflections of 90°, or right-angle bends, in ducts are commonly designated as elbows, and most of the data available on bend losses are the result of laboratory tests[4] on elbows in small ducts made under conditions that facilitated the test work without necessarily producing normal flow conditions at the entrance to the elbow or complete expansion of the flow beyond the elbow; and many of the published results include friction losses for four to ten or more diameters of test duct - elbow and following duct of varying length - involved in the test installation. A few results for right-angle bends in mine airways[5] are available, but these results are somewhat uncertain on account of the variable areas of airways involved in test zones and the details of the required construction.

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[4] Harding, Louis A., The Flow of Air in Heating and Ventilating Ducts: Trans. Am. Soc. Heat. and Vent. Eng., vol. 19, 1913, pp. 219-227.
Bussey, Frank L., Loss of Pressure Due to Elbows in the Transmission of Air Through Pipes or Ducts: Trans. Am. Soc. Heat. and Vent. Eng., vol. 19, 1913, pp. 367-376.
Willard, A. C., Report on Hudson River Vehicular Tunnel Ventilation Investigation, by the University of Illinois Engineering Experiment Station, for the New York State and New Jersey Interstate Bridge and Tunnel Commissions: prepared Jan., 1922, but not published.
McElroy, G. E., and Richardson, A. S., Experiments on Fan-Pipe Installations at Butte, Montana: Rept. of Investigations 2509, Bureau of Mines, July, 1923, pp. 10-11.
Wirt, Loring, New Data for the Design of Elbows in Duct Systems: Gen. Elec. Rev., vol. 30, 1927, pp. 286-296.
Cooke, W. E., and Statham, I. C. F., The Resistance to Flow of Air at Bends and in Straight Airways: Trans. Inst. Min. Eng. (London), vol. 77, 1929, pp. 188-212.

[5] Greenwald, H. P., and McElroy, G. E., Coal-Mine Ventilation Factors: Bull. 285, Bureau of Mines, 1929, pp. 66-69.
McElroy, G. E., and Richardson, A. S., Resistance of Metal-Mine Airways: Bull. 261, Bureau of Mines, 1927, pp. 133-134.
Cooke, W. E., and Statham, I. C. F. Work cited.

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The common type of bend in mine airways is one having sharp intersections of the walls at the inner and outer corners, a condition that gives a maximum shock pressure loss. Bends in ducts usually have the inner and outer corners rounded on concentric curves because it has been found that the shock loss decreases as the degree of curvature is increased. The degree of curvature is commonly designated by the ratio of the center line radius to the width in the plane of turning, termed the "radius ratio," or R/D in Figure 3. Just as it is harder to bend a plank on the wide dimension than on the narrow dimension, so it is easier as respects shock loss to have the air flow turn through the larger dimension of the airway than through the smaller dimension. In rectangular airways, therefore, the ratio of the side on which turning takes place to the other dimension is termed the "aspect ratio," or W/D in Figure 3, a term borrowed from aeronautics by Wirt, whose tests are about all the data we have on this factor of bend losses.

A careful consideration of all the available data on the effect of the radius ratio shows an extremely large variation in the results reported by different investigators, which is approximately 100 per cent even after corrections have been made for included friction pressure losses ($X = 0.02$ per diameter approximately for smooth ducts) and aspect ratio variations. Analyses of test installation conditions reveal causes for many of these seeming inconsistencies but no way of correcting the data to a basis comparable to normal air flow conditions both preceding and following the bend. Wirt's careful provision of uniform-velocity distribution at the elbow entrance, although provided to insure accuracy, apparently had the opposite effect and destroyed not only the absolute accuracy of his results for application to normal flow conditions of nonuniform velocity distribution, but even their relative value in at least one instance. Wirt found that a square outer corner had about 10 per cent less shock loss than a rounded outer corner and this fact was widely acclaimed in the technical press as a startling example of a case where test results refuted ordinary reasoning. The result is startling but apparently due to the test condition of uniform velocities at entrance to the elbows since many other tests, for normal flow conditions, show that the shock loss for an elbow with square inner and outer corners is about 20 per cent greater than for one having a square inner corner and rounded outer corner of conventional type; and the bureau's tests in coal-mine airways show that the difference in shock loss for the two conditions increases as the radius of the inner corner is increased. However, Wirt's tests developed considerable data on flow conditions in elbows and, of greater practical importance, the relative effect of the aspect ratio, which he put to immediate practical application in the development of the "blade" turn, a form of elbow in which curved blades inserted in a square-cornered elbow divide the single turn into the equivalent of a series of turns with radius ratios and aspect ratios favorable to low shock losses.

Effect of Radius Ratio

For the normal type of 90° bend, Figure 4 A, where the inner radius is one-half the width less than the center line radius and the outer radius is one-half the width greater, the shock loss due to the bend apparently varies inversely as the square of the radius ratio and, for an aspect ratio of one (round or square section), the shock factor for this normal type of right-angle bend may be taken as approximately:

$$X = \frac{0.25}{r^2} \qquad (8)$$

where r is the radius ratio, or R/D in Figure 3.

The constant 0.25 is taken as a fair approximation of the most reliable test results for normal flow conditions in round and square airways. Separate sets of data indicate constants varying from 0.18 to 0.40.

The minimum value of r is 0.5 for the condition of square inner corner and an outer radius equal to the width, and $X = 1.0$. Good results are obtained where $r = 1.5$ and there is little practical advantage in exceeding $r = 2.0$ -- that is, a center-line radius greater than twice the width or diameter. For the "square" bend, Figure 4-B, r is also 0.5 where both inner and outer corners are square and most of the test results on small ducts indicate an increased shock loss over the normal type of rounded outer corner, and a shock factor of about $X = 1.20$. The bureau's tests on mine airways also show that, as the radius of the inner corner increases with the outer corner square, the shock loss decreases only about as fast as the value of r increases, or that

$$X = \frac{0.60}{r} \qquad (9)$$

for this special case of square outer corner (figure 4-B).

For the case of the "crowded" elbow (fig. 4-C) where the outer radius is made shorter than the normal concentric design - that is, less than one width longer than the inner radius - Willard's tests show that the pressure loss, while still varying inversely as the square of the radius ratio, is larger than for the normal design; 40 per cent larger when the outer radius is but 75 per cent of the normal radius concentric with the inner radius.

The bureau's tests with the inner corner of the airway cut off on a 45° bevel and outer corner square (fig. 4-D) a common condition at the top of mine air-shafts - show that the loss is about the same as for a square bend with a radial curve on the inner corner touching the walls at the same points as the bevel. A few tests on segmental elbows (fig. 4-E) indicate that the losses can be computed on the basis of the circumscribed radii, with a small allowance for "crowding" on the outer corner.

When it is desired to reduce the loss at a bend where a square inner corner can not be displaced, a form of construction based on the fact that the air crowds to the outer two-thirds of the bend in turning, and termed a "Venturi" bend, may be used. As shown in Figure 4-F, the area at the bend is smoothly reduced to about two-thirds, and is gradually brought back to normal area following the bend. According to Bussey, this form was suggested by Konrad Meier in his book "Mechanics of Heating and Ventilating." It has been the subject of a number of tests which indicate that the losses are approximately equivalent to those for a normal bend with a radius ratio of about 0.8 to 0.9, depending on the details of construction.

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Effect of Aspect Ratio

Wirt's test data give the effect of aspect ratio on shock pressure losses for single right-angle elbows in terms of a factor expressing the relation of the loss at other aspect ratios to that with aspect ratio of 1. For ratios greater than 1, his data indicate that the shock factors vary approximately inversely as the square root of the aspect ratio. For ratios less than 1, his test data show a rapid departure from the curve expressing the foregoing relationship, but considering the latter as a possible result of uniform-velocity test conditions it seems best to hold to a simple relation between aspect ratio and shock factor until more data are available, and the effect of aspect ratio may be found approximately from the formula,

$$X = \frac{X'}{\sqrt{a}} \qquad (10)$$

where X' is the shock factor for the same type of bend with an aspect ratio of 1 (square section)
and a is the aspect ratio, or W/D in Figure 3.

Bends with aspect ratios greater than 1 have been termed "bucket" bends, and those with a ratio less than 1, "flat" bends. Bucket bends are always to be preferred, but it is a fact that the bend at the top of most mine air-shafts will be found to be a flat bend rather than a bucket bend, even though the increase in power cost in most cases greatly exceeds the decrease in construction cost, except for temporary installations.

Effect of Vanes

A number of tests have been made in which vanes have been installed at right-angle bends for reducing the shock loss. Such vanes introduce some resistance to flow by their added friction surfaces and obstructing edges, but act to divide the single bend into a number of separate bends, each deflecting a proportional part of the total flow, that have better radius and aspect ratios than the original single bend; and the net result is decreased shock loss. The vanes are commonly installed concentrically to the radius of the inner corner, and tests have shown that the best construction for a single vane in the normal type of bend is about one-third of the width from this corner. The probable effect of a vane, or vanes, can be roughly determined by calculation from radius and aspect ratios, but as allowance must be made for the increased losses due to the added rubbing surfaces and obstructions, the test results check calculated losses relatively rather than absolutely.

A good example of the use of vanes in improving radius and aspect ratios and thereby reducing the normal loss is the "blade turn" (fig. 4-G) developed by Wirt, in which short curved blades are installed centered on the diagonal of the turn and divide it into the equivalent of numerous bends with high radius and aspect ratios. With an elbow that had a radius ratio of 0.67 and an aspect ratio of 1.0, the installation of 11 short, curved, sheet-metal vanes, which divided the turn into 12 equal segments having radius ratios of 1.5 and aspect ratios of 12, reduced the (abnormally high) shock loss of 0.90 velocity pressure (X = 0.90) to 0.22 velocity pressure (X = 0.22).

The addition of straight extensions, either upstream or downstream, to radial vanes has always shown an increased loss, in experiments, over the condition of radial vanes without such extensions.

Closely-Spaced Right-Angle Bends

Since the expansion of the contracted air stream at the departure side of a bend takes place over a considerable distance downstream from the bend, it is only natural that tests on closely spaced bends - bends so close to each other that the opportunity for full expansion is lacking - should show test results differing from those of single bends, as the case actually is. The same effect has been noted in aeronautics and other forms of air flow and is often referred to as the "shielding effect" of one object on another.

From the bureau's test data on closely-spaced right-angle bends in the same plane (Bull. 285, pp. 80-89), it appears that where the deflection of both bends is in the same direction the lack of complete expansion at the first bend not only reduces its shock loss below normal, but, by providing higher than normal velocities at the outer corner of the second bend, also results in a lower than normal degree of contraction at the departure from the second bend and thus reduces its shock loss to less than the normal. This combination has been termed a "double" right-angle bend (fig. 4-H).

Where the flow is deflected at the second bend in a direction opposite to that of the first bend, the combination is termed a "reverse" bend (fig. 4-I). Both Bussey's and the bureau's test data indicate that while lack of complete expansion may reduce the loss at the first bend, that of the second bend is increased by the higher than normal velocities at its inner corner, with the result that the total shock loss for a reverse bend is greater than the sum of the normals for both bends.

The downstream distance required for full expansion is not known, but the maximum is probably at least 10 diameters or widths and may be more, and is affected to some extent by the velocity of flow. Bureau tests in coal-mine airways 6 feet high and 9 feet wide with right-angle bends on 50-foot centers showed about 20 per cent greater loss for square-cornered reverse bends than for double bends of the same type, indicating that the expansion was still far from complete in 4.6 widths for that high rate of pressure loss. The same series of tests showed, by rough segregation of the losses for both bends of a double right angle, that the distance required for full expansion is materially decreased as the rate of pressure loss decreases, as would be expected, since the rate of pressure loss is dependent on the degree of contraction.

Where two closely spaced bends are not in the same plane, the combination is referred to as a "compound" bend (fig. 4-J). Here the higher than normal velocities at entrance to the second bend, resulting from incomplete expansion following the first bend, affect both inner and outer corners of the second bend equally. Although no complete test data are available, it can be assumed that the loss at the first bend would be lower than the normal and that of the second bend higher than the normal; and that, in all probability, the total loss for the combination would be approximately equal to the sum of the normal losses for the two single bends.

Effect of Angle of Deflection

Few test data are available for deflections other than 90°. Weisbach's[6] rather meticulous formula for square-cornered bends,

$$X = 0.9457 \sin^2 \tfrac{1}{2} i + 2.047 \sin^4 \tfrac{1}{2} i, \qquad (11)$$

indicates that the shock pressure loss varies practically as the 2.38 power of the angle of deflection, while the recent data of Cooke and Statham[7] for square-cornered bends indicate that it varies almost exactly as the square of the angle of deflection; and scattered test data also indicate that the square relation holds. Cooke and Statham's data on bends having radius ratios of 1 to 4, and thus low rates of pressure loss, give variable relations, but an analysis and comparison of their data indicate the strong probability that this result is due to inadequate deductions for friction pressure losses. It therefore seems best to assume that the effect of the angle of deflection on the shock loss may be determined approximately by the formula,

$$X = \frac{i^2}{(90)^2} X' = \frac{i^2}{8100} X', \qquad (12)$$

where X' is the shock factor for a right-angle bend of the same design, radius ratio, and aspect ratio,

and i is the angle of deflection, or exterior angle of the center lines, in degrees.

General Formulas for Shock Factors for Uniform-Area Bends

Since we have no reliable data for the effects of radius ratio and aspect ratio for deflections of other than 90°, we can only assume that the relative effects would be the same as for 90° deflections. From the incomplete and inconsistent data now available, it would appear that best complete formulas for computing approximate shock factors for shock losses due to bends in uniform-area mine airways are,

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[6] Peele, Robert, Mining Engineer's Handbook: 1st ed., New York, 1918, p. 1031.

[7] See reference 2.

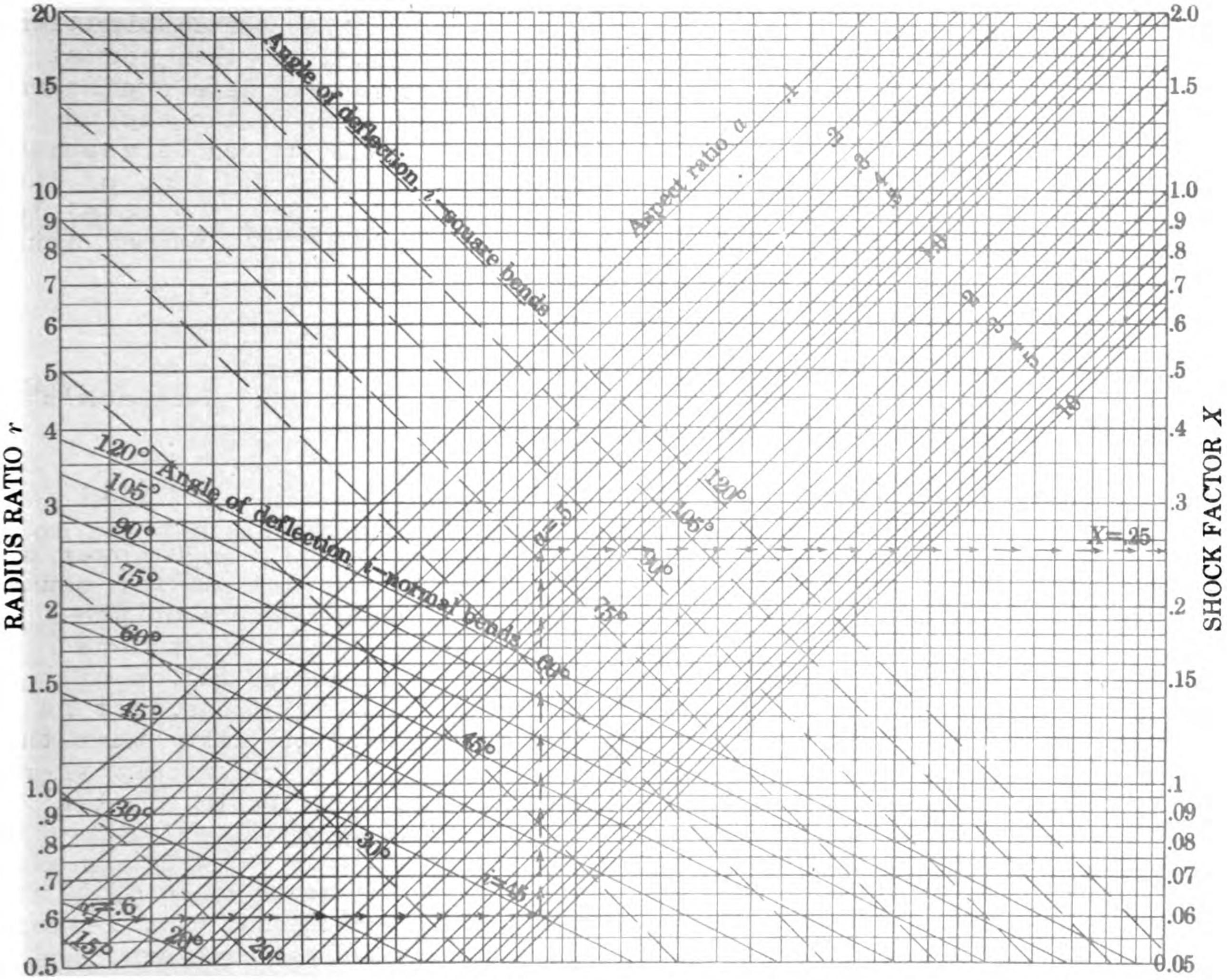
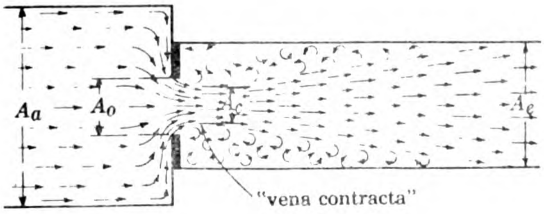


Figure 5.- Chart for determining shock factors, or shock pressure losses in terms of equivalent velocity pressures, for bends in airways of uniform area



$$\frac{A_c}{A_o} = c = \text{coefficient of contraction}$$

$$\frac{A_o}{A_a} = N_c = \text{ratio of contraction (areas)}$$

$$\frac{A_o}{A_e} = N_e = \text{ratio of expansion (areas)}$$

Figure 6.- Sketch showing general conditions of flow and defining characteristics of area changes in airways

$$X = \frac{0.25\ i^2}{r^2 \sqrt{a}\ 8100} \qquad (13)$$

for the normal type of concentric-radii bend, and

$$X = \frac{0.60\ i^2}{r \sqrt{a}\ 8100} \qquad (14)$$

for "square" bends, or bends with a square outer corner. These reduce to

$$X = \frac{0.25}{r^2 \sqrt{a}} \qquad (15)$$

and

$$X = \frac{0.60}{r \sqrt{a}} \qquad (16)$$

for right-angle bends in rectangular airways, and to

$$X = \frac{0.25}{r^2} \qquad (17)$$

and

$$X = \frac{0.60}{r} \qquad (18)$$

for right-angle bends in square or round airways. Little is known regarding the factors for abnormal types, although a few such types have been discussed in this paper under "Effect of Radius Ratio." For the most common type of abnormal bend encountered in mine airways - that where the areas at entrance and departure are unequal - we unfortunately have no test data on which to base a rational method of computing the shock factors for the shock losses.

Chart for Determining Shock Factors for Bends

In Figure 5, a graphic chart is presented for the rapid determination of shock factors for shock losses due to "normal" and "square" bends in mine airways of uniform area. This is based on formulas (13) and (14). The method of using the chart is shown by the dotted-line solution of an example, with arrows indicating the direction of procedure. In the example solved in the chart, it is shown that, when the radius ratio of a normal bend is 0.6, the angle of deflection 45°, and the aspect ratio 0.5, the shock factor is 0.25. In using the chart, it is important to note that the full lines for angle of deflection should be used for the normal type of concentric-radii bend, whereas the dash lines should be used for bends with square outer corner.

Shock Factors for Area Changes

The area of the cross section of airways or ducts changes frequently in any ventilating system and each change requires the interchange of pressure from the velocity pressure form to the static pressure form, or vice versa. These interchanges are not 100 per cent efficient and some of the total pressure of the air stream is lost at each change, the magnitude of the loss depending primarily on the degree of abruptness of the change in area of the air stream, which may take place because of changes in the dimensions of the airway itself, or because of conditions that cause the air flow temporarily to occupy only part of the total area of the airway.

The shock pressure losses caused by area changes have been found to bear a constant ratio to the velocity pressure; absolutely so for the more abrupt changes such as orifices and practically so for the less abrupt changes. For the latter, slight variations, similar to those found with friction factors and shock factors for deflections, accompany variations in flow conditions, but they are not of sufficient magnitude to be taken into consideration here.

The pressure losses due to the normal average change in area between successive sections of an airway should properly be included, or allowed for, on a shock pressure loss basis, but the effects are small and not separable from the friction losses with which they have always been included in determining the range between the maximum and minimum values of the friction factors for clean straight airways; and there is no doubt that area changes have much to do in determining the spread between maximum and minimum values assigned to friction factors.

Intermittent Obstructions

Mine airways often contain intermittent obstructions that change the area of cross section under conditions where the individual shock losses are so small that they practically defy computation and where it is more convenient to determine directly the average total shock loss per unit of length, which the data[8] available permit with a very rough degree of approximation, as follows:

Slight degree: $X = 0.1$ per 100 feet; trolley box, water box, large flanged pipe, occasional small falls of roof, occasional small crossbars, hangers, props, etc.

Moderate degree: $X = 0.3$ per 100 feet; large fan pipes or tubings, occasional large crossbars or heavy hangers, frequent small falls, occasional constrictions, etc.

High degree: $X = 1.0$ per 100 feet; combinations of obstructions given above, large falls, occasional storage piles of timbers or pipes, closely set crossbars, props or constrictions, etc.

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[8] McElroy, G. E., and Richardson, A. S., Resistance of Metal Mine Airways: Bull. 261, Bureau of Mines, 1927, p. 134.

These values are for average areas determined by subtracting the area occupied by the obstruction where the latter is continuous and of appreciable size. For the very high degrees of obstruction occasionally found in mine airways, it is impossible to set even approximate limits, as the normal characteristics become of minor importance in comparison with the characteristics of the obstructions and each case must be computed by analyzing its separate features and separately calculating the friction and shock losses involved.

Formulas for Shock Factors for Symmetrical Changes of Area

The available test data indicate that the pressure losses for area changes are practically all due to shock pressure loss caused by a faster stream expanding into a larger area and slower stream; there appears to be no perceptible pressure loss in converging air streams due to the converging itself, but the converging of the air stream causes it to contract beyond the edge of the constriction, giving rise to a condition at constrictions in area known as the "vena contracta," as illustrated in Figure 6. The area of cross section of the air stream is a minimum immediately following the edge of the constriction, and the shock loss is that caused by expansion from this area to the full area of the following duct with consequent lowering of the velocity and imperfect conversion of the difference of the velocity pressures required by the two areas.

General Formulas for Abrupt Expansion.- The shock pressure loss occasioned by a faster moving stream expanding symmetrically and abruptly to a slower moving stream is given in all elementary hydraulics as equivalent to the velocity pressure corresponding to the difference of the two velocities involved. We have no such general law for unsymmetrical expansion and the following discussion will therefore apply only to symmetrical expansion unless otherwise stated. The shock loss for symmetrical expansion at any density, d, is therefore

$$H = 0.0^6831\ d(V_c - V_e)^2 \qquad (19)$$

and at standard air density of 0.075 pound per cubic foot, is

$$H = 0.0^7623\ (V_c - V_e)^2 \qquad (20)$$

where H is the pressure loss in inches of water
and V_c and V_e are the velocities in feet per minute at the smaller (contracted) and larger (expanded) areas respectively.

Where the actual velocities are known, the shock loss may be computed directly from this formula, but for general purposes it is desirable to have the loss in terms of equivalent velocity pressures, or shock factors, based on actual airway areas or ratios of airway areas.

190

If A_c and A_e represent the smaller and larger areas, respectively, involved in the expansion, then, since the quantity of flow is the same at each area, we have the relation $A_cV_c = A_eV_e$ from which may be obtained

$$(V_c - V_e)^2 = \left(\frac{A_e}{A_c} - 1\right)^2 V_e^2 \tag{21}$$

and

$$(V_c - V_e)^2 = \left(1 - \frac{A_c}{A_e}\right)^2 V_c^2 \tag{22}$$

and, with H_{ve} and H_{vc} representing the velocity pressures corresponding to velocities V_e and V_c, respectively,

$$H = \left(\frac{A_e}{A_c} - 1\right)^2 H_{ve} \tag{23}$$

and

$$H = \left(1 - \frac{A_c}{A_e}\right)^2 H_{vc} \tag{24}$$

Where the actual areas involved are known, as in simple expansion, these formulas can be used directly for computing the shock loss, or shock factors may be computed from the area ratios; but in the more general case of expansion following contraction, A_c is the area at the "vena contracta" and can not be measured directly but must be determined from experimental data. For this reason it is desirable to develop more general formulas that may be applied in all cases.

The general case of expansion following contraction is represented in Figure 6. Four areas are involved: A_a, the area preceding the contraction; A_o, the area at the contraction or orifice; A_c, the area occupied by the air flow at the "vena contracta;" and A_e, the area following the contraction, to which expansion occurs. If we designate the ratio of air-flow contraction at the constricted area by c, usually termed the "coefficient of contraction," and the ratio of expansion areas by N_e, then $\frac{A_c}{A_o} = c$, and $\frac{A_o}{A_e} = N_e$. Using these new designations for area ratios, we have

$$\frac{A_e}{A_c} = \frac{A_e}{c\ A_o} = \frac{1}{c\ N_e}, \tag{25}$$

and

$$\frac{A_c}{A_e} = \frac{c\ A_o}{A_e} = c\ N_e, \tag{26}$$

and, by substituting in (23) and (24),

$$H = \left(\frac{1}{c\,N_e} - 1\right)^2 H_{ve}, \qquad (27)$$

and

$$H = (1 - c\,N_e)^2\,H_{vc}. \qquad (28)$$

The latter form is not directly usable, since it involves an unknown velocity pressure, that at the "vena contracta." However, with quantity of flow constant, velocity pressures vary inversely as the square of the areas involved, or ratio of areas, and, with H_{vo} denoting the velocity pressure at the contracted area A_o,

$$H_{vc} = \left(\frac{1}{c}\right)^2 H_{vo}; \qquad (29)$$

so, by substitution in (28),

$$H = (1 - c\,N_e)^2 \left(\frac{1}{c}\right)^2 H_{vo} = \left(\frac{1}{c} - N_e\right)^2 H_{vo}. \qquad (30)$$

Although it is not directly involved in the pressure loss, it is often convenient to express the pressure loss in terms of the velocity pressure corresponding to the area, A_a, preceding the contraction. If we let N_c denote the ratio of the contracted area to the area preceding contraction, or $\frac{A_o}{A_a}$, and H_{va} the velocity pressure corresponding to the area A_a preceding contraction, then from the inverse relation of velocity pressures to the square of the area ratio we have,

$$H_{vo} = \frac{H_{va}}{N_c^2}, \qquad (31)$$

and, by substituting this value of H_{vo} in (30),

$$H = \frac{\left(\frac{1}{c} - N_e\right)^2}{N_c^2}\,H_{va}. \qquad (32)$$

The shock loss is seen to be a constant number of velocity pressures for constant conditions and, in terms of velocity pressures corresponding to three different airway areas involved, is

$$H = X_e\,H_{ve} = X_o\,H_{vo} = X_a\,H_{va}, \qquad (33)$$

where X_e, X_o and X_a are the shock factors based on the area after expansion, the area at the constriction, and the area preceding contraction, or A_e, A_o and A_a, respectively, in Figure 6. Convenience alone usually dictates which factor should be used. From (27), (30), and (32) the shock factors are,

$$X_e = (\frac{1}{cN_e} - 1)^2, \tag{34}$$

$$X_o = (\frac{1}{c} - N_e)^2, \tag{35}$$

and

$$X_c = \frac{(\frac{1}{c} - N_e)^2}{N_c^2} \tag{36}$$

for general application to conditions where the shock loss is due to abrupt symmetrical expansion in the area actually occupied by the flow.

General Formula for Gradual Expansion.- Where the expansion of the area occupied by the air stream is gradual and symmetrical, it has been found that the shock loss is a constant ratio of that for abrupt symmetrical expansion; and the required shock factors are

$$X' = y\,X, \tag{37}$$

where X' represents the shock factors for gradual expansion corresponding to values of X for abrupt expansion, and y is an empirical factor based on experiments.

Values of y vary with the included angle, or slope, of the walls, and values of y, available from experiments, are plotted in Figure 7 against the included angle. The "Fan Engineering" handbook[9] data indicate that angles greater than 60° are no better than abrupt expansion. These data do not show, however, that the normal angle of symmetrical expansion of air flow is on about 7°, above and below which value the shock loss is increased. Brigg's[10] data do bring out this fact, which is proved by a wealth of corroborating experimental data on air flow, and also indicate that conditions of non-symmetrical expansion have an effect on the shock loss, since the minimum is at 11° instead of 7° for 2-sided expansion, and it is probable that tests for one-sided rectangular expansion would show a still higher value for the optimum angle of expansion. The values of y plotted in Figure 7 for Briggs' data on 2-sided expansion were derived through the formulas for symmetrical (4-sided) expansion and can therefore be used with them, although not with any great degree of certainty.

Shock losses for gradual expansion depend on N_e as well as the experimentally determined values of y, and N_e is directly related to the slope of the sides and the length in diameters of the diverging section. The relations of slope to included angle, and of N_e to length and included angle, are also plotted, for convenience, in Figure 7.

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[9] Buffalo Forge Co., Fan Engineering: 2d ed., Buffalo, 1925, p. 68.

[10] Briggs, Henry, and Williamson, J. N., An Experimental Study of Fan Evasees: Trans. Inst. Min. Eng., London, vol. 68, 1924-25, pp. 323-344.

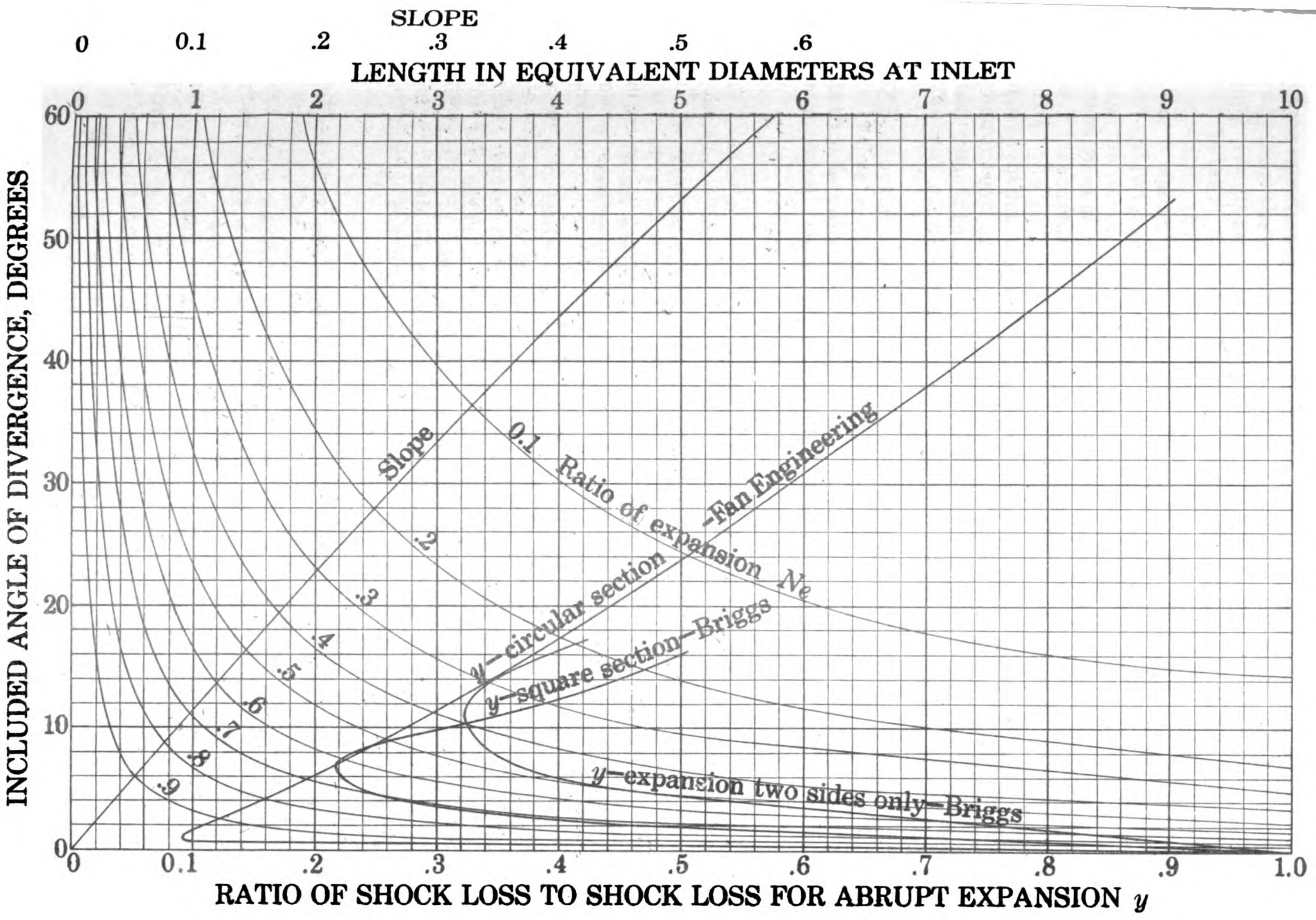

Figure 7.— Chart of data for gradual symmetrical expansion at diverging sections of airways, for included angles of 0° to 60°

Coefficient of Contraction.- Inspection of the formulas given for determining shock factors for symmetrical area changes shows that, in all cases of contraction, the coefficient of contraction, c, is involved. This coefficient, since it involves an area, A_c (fig. 6), that can not be measured, must always be calculated. As here used, it is a calculated figure determined by considering the total pressure loss at the condition, in excess of the normal friction loss, as a shock loss due entirely to symmetrical expansion, as it undoubtedly is, and computing the value of c accordingly. Values of the coefficient of contraction as given by various investigators do not always have this same meaning, as direct pressure measurements have sometimes led to a segregation of shock losses as occurring both before and after the "vena contracta." Those found preceding the constriction have always been so small that their actual existence is doubtful and, in any event, are included in the loss as determined by the coefficient of contraction as here used, which Weeks[11] designates as the "virtual" coefficient of contraction, and which others have termed the "coefficient of discharge."

Contraction Factors.- The author has found[12] by analyzing the results of his own tests and those of others, that, with other conditions constant, there is a definite relation between the ratio of contraction areas and the coefficient of contraction, which may be expressed thus:

$$c = \sqrt{\frac{1}{Z - ZN_c^2 + N_c^2}} \qquad (38)$$

where N_c is the ratio of contraction, or $\frac{A_o}{A_a}$ in Figure 6,

and Z is an empirical factor, which will be designated as the "contraction factor."

Values of Z calculated from test data, in which a series of coefficients are given for use in a particular formula, are usually practically identical for the middle range of values of N_c and depart from a practically uniform value only for the extreme ranges of N_c, in which ranges experimental accuracy is most difficult to obtain. For many of the conditions of contraction encountered, such as orifices in ducts of uniform area, the values of the ratios N_c and N_e are identical, but such is not always the case, particularly as respects mine airways.

Values of Z are particularly affected by the edge condition at the constricted area, by the degree of abruptness of contraction, and by the form of contraction as regards symmetry. Practically all of the data available are for symmetrical contractions in which the areas of cross section are similar figures and centered as respects each other, and the data to be given are for such symmetrical layouts unless otherwise stated.

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[11] Weeks, W. S., The Air Current Regulator: Trans. Am. Inst. Min. Eng., vol. 76, 1928, p. 138.

[12] McElroy, G. E., Ratio of Opening of Fan Performance: Jour. Am. Soc. Heat. and Vent. Eng., vol. 24, 1928, pp. 784-785.

Abrupt Symmetrical Contraction.- A large amount of data on abrupt and gradual contractions and expansions is given in the handbook "Fan Engineering,"[13] and includes coefficients and formulas for various conditions. Analysis of these and similar data indicates that there is very good agreement of the Z values for abrupt contraction obtained in various sets of tests, particularly when test results have been corrected for included friction pressure losses for several diameters of the duct used in the test installations. Minor differences are evident which may be sufficient to affect the accuracy of air measurements based on static pressure changes, but are not of sufficient magnitude to affect seriously the calculation of shock losses for mine airways.

For free contraction to a sharp edge, as at the entrance to a plain open pipe, Z averages 3.80. With a flat surface extending from the sharp edge at right angles to the direction of flow, a very common condition represented by mine airway entrances, by abrupt contraction in ducts and airways and by orifice plates, Z is about 2.5 for ordinary degrees of sharpness as obtained with square-edged plates, although the very sharp edges of thin orifice plates used for air measurement give a practically constant value of Z of 2.70. The exact edge condition has a large influence on the contraction factor and for the normal sharp-edges found in mine constructions, which will be referred to hereafter as "square" edges, a Z value of 2.5 is at least sufficiently high and generally applicable. If the edge is rounded, the shock loss is greatly reduced, but since the edge condition is not susceptible to rigid specification, this form is not applicable for air measurement, and there are therefore few data available for determining average Z values. For a well-rounded edge comparable to that presented by a round timber in a mine airway, the value of Z is estimated from scanty data as about 1.5, and for lack of a better-substantiated value, this will be used in determining shock factors for round-edged conditions in mine airways.

Although definite data are lacking, it seems probable that the same approximate Z factor of 1.5 can be applied where the edge is beveled to about the same degree - that is, to the extent that the bend would be circumscribed by a quadrant of a similar circular section. Most of the shock factors directly available apply to very sharp orifice-edge conditions, but no attempt will be made here to show shock factors for this type of edge condition, since we are concerned with pressure losses rather than air measurement.

Gradual Symmetrical Contraction.- If the contraction in area is made gradually instead of abruptly, the degree of contraction of the flow at the "vena contracta" is reduced and the shock loss also. Where the decrease in area is accomplished at a uniform rate, as in a well-rounded entrance or in the "standard" orifice, there is very little contraction of the flow and an average value of Z for the best designs is about 1.05. This form can be considered as representing a definite edge condition and will be referred to hereafter as a "formed" edge.

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[13] See reference 9, pp. 60-72.

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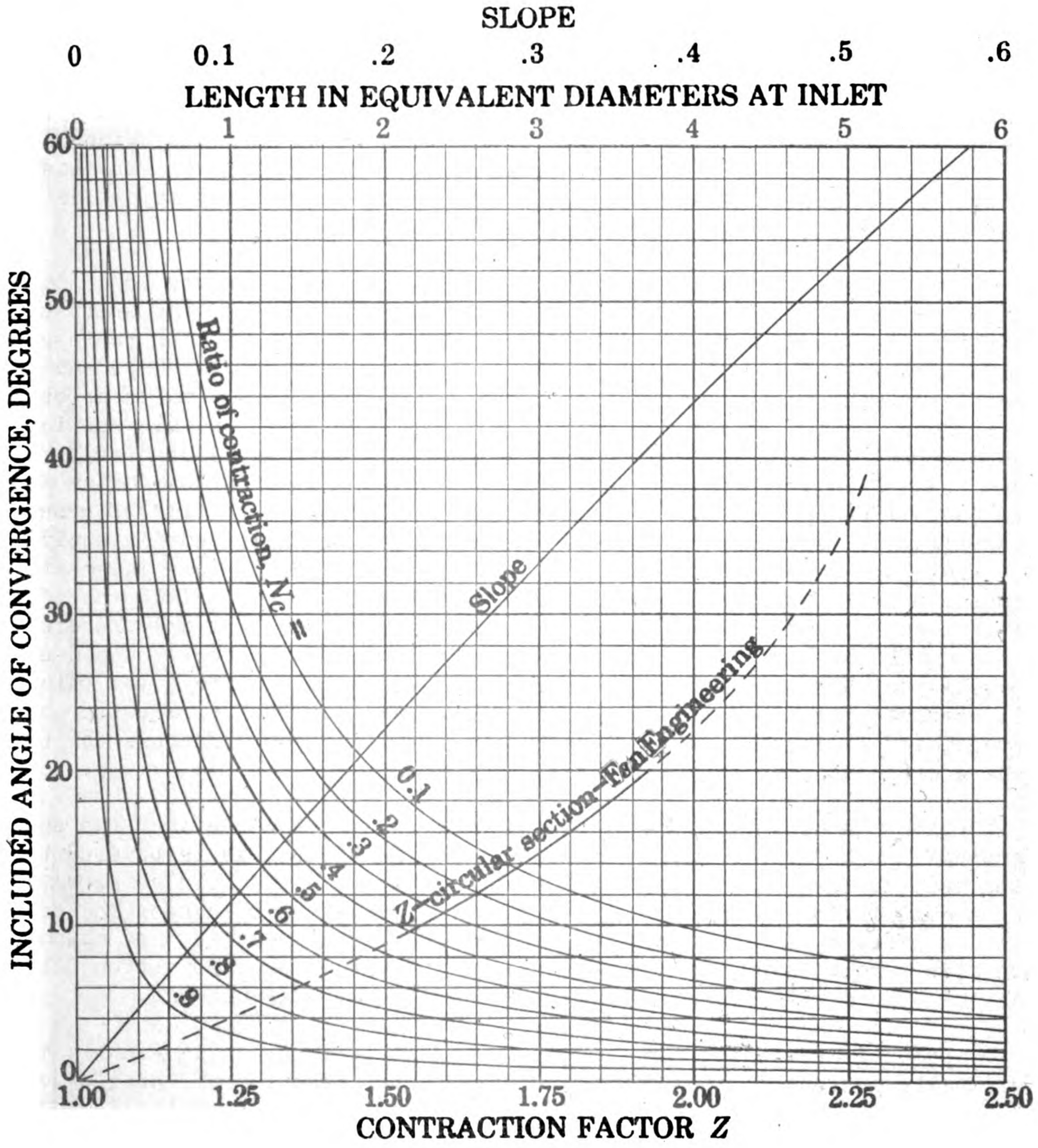

Figure 8.- Chart of data for gradual symmetrical contraction at converging sections of airways for included angles of 0° to 60°

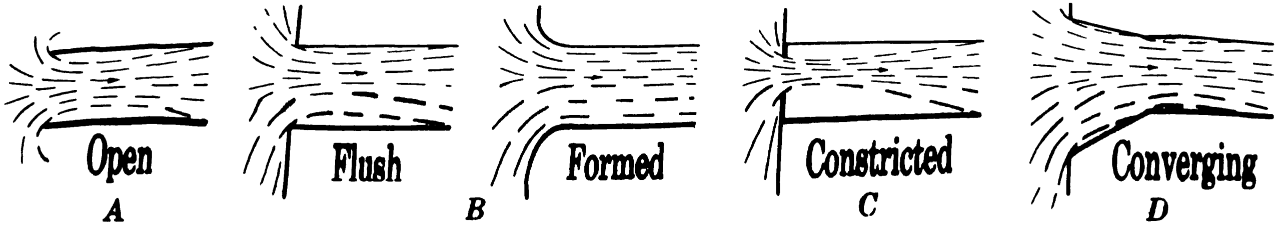

Figure 9.- Flow conditions at area changes at entrance to airways

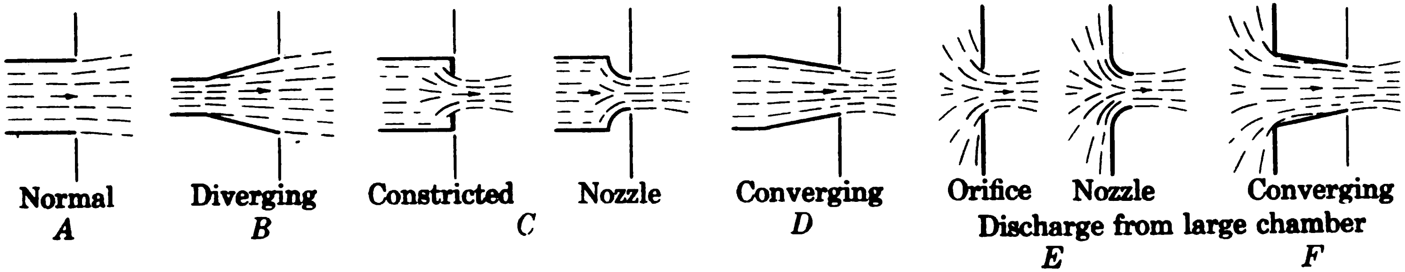

Figure 10.- Flow conditions at area changes at discharge from airways

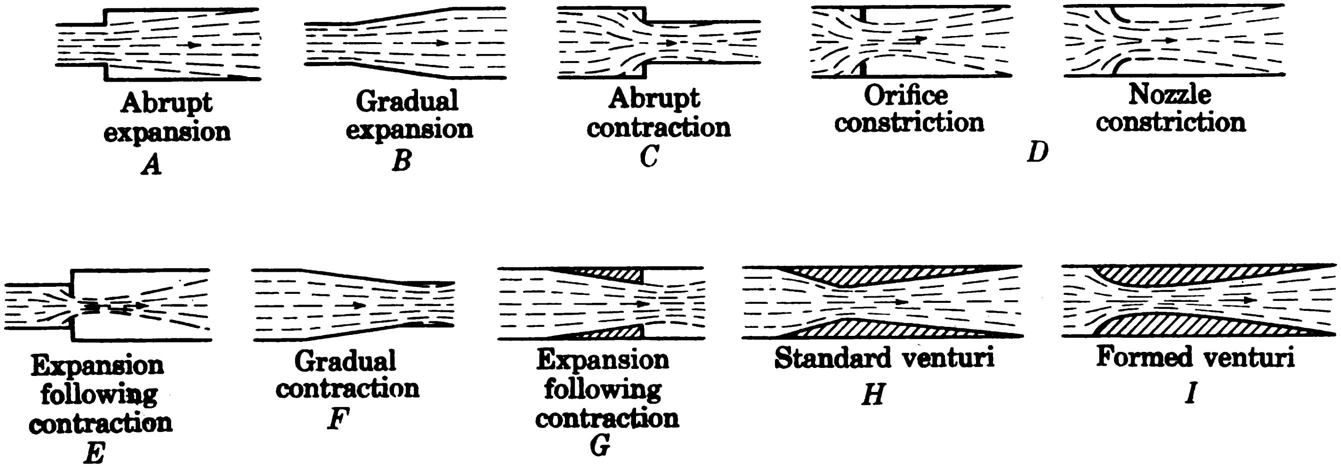

Figure 11.- Flow conditions at area changes within airways

For walls converging on a uniform slope, data are available only for the range of 10° to 20° included angle (Fan Engineering, p. 65) and assumed to be for a sharp edge. The calculated Z values are plotted against included angle in Figure 8, and range from 1.57 for 10° to 1.93 for 20°. At 0°, Z would be 1.0 and for abrupt contraction of 180° it would be about 2.5. The slope of the curve, however, indicates that the value of 2.5 is probably closely approximated somewhere between 45° and 60° and that greater degrees of included angle of convergence are no better, as regards shock loss, than abrupt contraction.

Shock Factors for Symmetrical Area Changes

Installation conditions may be considered in three groups for the purpose of presenting data on shock factors: (1) Entrance to an airway, Figure 9; (2) discharge from an airway to the atmosphere, Figure 10; and (3) within an airway, Figure 11. In discussing the various shock factors required, it is, however, more convenient to depart from this grouping and base the discussion on the conditions of expansion and contraction. Values of the shock factors corresponding to the generally applicable contraction factors of 2.5 for square edge, 1.5 for rounded edge, and 1.05 for a formed edge are tabulated in Table 1 for conditions such that either N_c or N_e have fixed values of 1 or 0, or $N_c = N_e$.

Simplified Formulas for Fixed Values of N_c and N_e.- Although the contraction factors for a particular type of contraction may be constant, the shock factors and pressure losses depend also on the actual values of the area ratios N_c and N_e involved in the installation. Their magnitude depends primarily on whether the flow expands abruptly or gradually or is contracted abruptly or gradually, but the range of required factors depends more particularly on whether N_c and N_e have variable or fixed values. These values are fixed to a large extent by the conditions of the installations, since the relation of the areas corresponding to A_a, A_o and A_e in the general case represented by Figure 6 may be such that either N_c or N_e may have fixed values of 1 or 0; and although the general formulas, (34) to (38), still apply, they reduce to simpler forms.

When $N_c = 1$, that is, when no contraction of the flow precedes expansion, Z and c are also 1, and the general forms reduce to

$$X_e = \left(\frac{1}{N_e} - 1\right)^2 \qquad (39)$$

and

$$X_a = X_o = (1 - N_e)^2. \qquad (40)$$

When $N_e = 1$, that is, when contraction is followed by a uniform area,

$$X_e = X_o = \left(\frac{1}{c} - 1\right)^2 \qquad (41)$$

and

$$X_a = \frac{\left(\frac{1}{c} - 1\right)^2}{N_c^2}. \qquad (42)$$

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Table 1.- Shock factors, or shock pressure losses in terms of equivalent velocity pressures, for symmetrical changes of area of airways for common conditions of abrupt[1] contraction and expansion in which the ratios of contraction (N_c) or expansion (N_e) are 1, 0, or equal to each other

Constant ratio and special formulas	Variable ratio, of contraction (N_c), or expansion (N_e)			1	.9	.8	.7	.6	.5	.4	.3	.2	.1	0
	Condition of area change	Contraction factor, Z	Shock factor based on area before contraction (or expansion), X_a; on area at contraction, X_o; and on area following expansion (or contraction), X_e											
$N_c = 1$	Abrupt expansion without preceding contraction.	(1.0)	$X_a=X_o$	0	0.010	0.040	0.090	0.160	0.250	0.360	0.490	0.640	0.810	1.0
$X_a=X_o=(1-N_e)^2$ $X_e=(\frac{1}{N_e}-1)^2$			X_e	0	.012	.063	.184	.445	1.00	2.25	4.99	16.0	81.0	∞
$N_c = 0$	Wall contraction to													
$X_o=(\frac{1}{c}-N_e)^2$	Square edge	2.50	X_o	0.340	0.462	0.608	0.774	0.960	1.17	1.39	1.54	1.90	2.19	2.50
$X_e=\frac{(\frac{1}{c}-N_e)^2}{N_e^2}$			X_e	.340	.569	.953	1.58	2.67	4.66	8.70	18.2	47.6	219	∞
	Round edge	2/1.50	X_o	.050	.105	.180	.275	.389	.524	.679	.854	1.05	1.26	1.50
$X_a=\infty$			X_e	.050	.130	.280	.561	1.08	2.10	4.24	9.49	26.2	126	∞
$c=\sqrt{\frac{1}{Z}}$	Formed edge	1.05	X_o	.001	.016	.051	.106	.181	.276	.391	.526	.681	.856	1.05
$N_e = 1$	Wall contraction to													
$X_e=X_o=(\frac{1}{c}-1)^2$	Square edge	2.50	X_a	0	0.022	0.091	0.220	0.446	0.839	1.59	3.21	7.92	33.2	∞
			$X_o=X_e$	0	.018	.053	.108	.161	.210	.254	.289	.317	.332	.338
$X_a=\frac{(\frac{1}{c}-1)^2}{N_c^2}$	Round edge	2/1.50	X_a	0	.003	.012	.030	.061	.120	.230	.471	1.18	4.96	∞
			$X_o=X_e$	0	.002	.007	.015	.022	.030	.037	.042	.047	.050	.050
	Formed edge	1.05	X_a	0				.001	.001	.003	.005	.015	.062	∞
			$X_o=X_e$	0								.001	.001	.001
	Obstruction with Square edge	2/5.00	X_a	0	.132	.495	1.13	2.19	4.00	7.41	14.8	36.0	151	∞
			$X_o=X_e$	0	.107	.317	.554	.787	1.00	1.19	1.33	1.44	1.51	1.53
	Round edge	2/3.00	X_a	0	.038	.152	.361	.723	1.35	2.54	5.14	12.5	52.7	∞
			$X_o=X_e$	0	.031	.097	.177	.260	.338	.406	.462	.501	.527	.536
	Formed edge	2/2.10	X_a	0	.012	.051	.127	.258	.503	.935	1.91	4.71	19.8	∞
			$X_o=X_e$	0	.010	.033	.062	.093	.126	.150	.171	.188	.198	.202

[illegible] in terms of equivalent velocity pressures, for symmetrical changes of area of airways for common conditions of abrupt[1] contraction and expansion in which the ratios of contraction (N_c) or expansion (N_e) are 1, 0, or equal to each other - Continued

Constant ratio and special[1] formulas	Variable ratio, of contraction (N_c), or expansion (N_e)			1	.9	.8	.7	.6	.5	.4	.3	.2	.1	0
	Condition of area change	Contraction factor, Z		Shock factor based on area before contraction (or expansion), X_a; on area at contraction, X_o; and on area following expansion (or contraction), X_e										
$N_e = 0$	Wall contraction to													
$X_o = \frac{1}{c^2}$	Square edge	2.50	X_a	1	1.59	2.41	3.60	5.45	8.50	14.1	26.3	61.1	249	∞
			X_o	1	1.29	1.54	1.77	1.96	2.13	2.26	2.36	2.44	2.49	2.50
$X_a = \frac{1}{c^2 N_c^2}$	Round edge	[2]1.50	X_a	1	1.35	1.84	2.56	3.67	5.50	8.88	16.2	37.0	150	∞
			X_o	1	1.10	1.18	1.26	1.32	1.38	1.42	1.45	1.48	1.50	1.50
$X_e = \infty$	Formed edge	1.05	X_a	1	1.25	1.59	2.09	2.86	4.15	6.51	11.6	26.3	105	∞
			X_o	1	1.01	1.02	1.03	1.03	1.04	1.04	1.04	1.05	1.05	1.05
$N_e = N_c (= N)$	Wall contraction to													
$X_o = (\frac{1}{c} - N)^2$	Square edge	2.50	$X_a = X_e$	0	0.068	0.304	0.807	1.78	3.67	7.61	17.0	46.4	218	∞
			X_o	0	.055	.195	.395	.641	.918	1.21	1.53	1.86	2.18	2.50
$X_a = X_e = \frac{(\frac{1}{c} - N)^2}{N^2}$	Round edge	[2]1.50	$X_a = X_e$	0	.027	.128	.361	.836	1.81	3.92	9.12	25.9	126	∞
			X_o	0	.021	.082	.177	.301	.453	.627	.820	1.03	1.26	1.50
	Formed edge	1.05	$X_a = X_e$	0	.014	.068	.199	.480	1.08	2.41	5.79	17.0	85.6	∞
			X_o	0	.011	.044	.098	.173	.269	.385	.521	.679	.856	1.05
	Obstruction with Square edge	[2]5.00	$X_a = X_e$	0	.224	.909	2.23	4.60	9.00	17.8	38.2	100	452	∞
			X_o	0	.182	.582	1.09	1.66	2.25	2.85	3.44	4.00	4.52	5.00
	Round edge	[2]3.00	$X_a = X_e$	0	.093	.409	1.06	2.30	4.68	9.57	21.1	56.9	264	∞
			X_o	0	.075	.262	.520	.828	1.17	1.53	1.90	2.27	2.64	3.00
	Formed edge	[2]2.10	$X_a = X_e$	0	.049	.227	.616	1.38	2.92	6.09	14.4	38.1	181	∞
			X_o	0	.040	.146	.302	.497	.730	.974	1.30	1.52	1.81	2.10

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[1] For gradual contraction, interpolate in table for value of Z from Figure 8. For gradual expansion, with or without preceeding contraction, multiply tabular values by Y from Figure 7.

[2] Tentative approximations only.

When $N_c = 0$, that is, when the area preceding contraction is so large that it may be considered to be infinite in comparison with the contracted area, the general form (38) for coefficient of contraction reduces to

$$c = \sqrt{\frac{1}{Z}}; \tag{43}$$

that is, the coefficient is constant for fixed types of contraction.

When $N_e = 0$, that is, when the area following the contraction is so large that it may be considered to be infinite in comparison with the contracted area, the general forms reduce to,

$$X_0 = \left(\frac{1}{c}\right)^2 \tag{44}$$

and

$$X_a = \left(\frac{1}{cN_c}\right)^2 . \tag{45}$$

When both N_c and N_e are 0, as in discharge through a small hole in a large plate, both (43) and (44) apply and,

$$X_o = Z . \tag{46}$$

When $N_c = 1$ and $N_e = 0$, which is the condition for unrestricted free discharge from a duct or airway, (40), (44) and (45) all reduce to

$$X_a = X_0 = 1 . \tag{47}$$

Abrupt Expansion.- Where no contraction of the flow precedes the abrupt expansion, we have what amounts to a special case of application of the general formulas which provide for such contraction, in which the value of N_c, Z and c is 1.0. There are only two common conditions of installation: In the airway (fig. 11-A) where N_e may have any value between 0 and 1, and formulas (39) and (40) apply; and at discharge into the atmosphere (fig. 10-A) where N_e is 0 and $X_a = 1$, from (47).

Gradual Expansion.- Where no contraction of the flow precedes gradual expansion, we also have what amounts to a special case of application of the general formulas which provide for such contraction, since the value of N_c, Z and c is 1.0; but the shock factor, from (37), is y times the factor for abrupt expansion as determined from (39) and (40), and y is derived from Figure 7, or a similar source.

The most common condition of installation is that within the airway (fig. 11-B). This form, the diverging connection or transformation, finds an important application in reducing pressure losses in mine airways by substituting gradual expansion for abrupt expansion. The same type of construction may be used at the discharge end of the airway (fig. 10-B), but gradual expansion is then followed by abrupt expansion, and the factors for this combined shock loss are different than for gradual expansion only, although they can be combined into single factors in terms of the normal airway area or the area at discharge. This form is also of great practical importance for reducing the pressure losses at the discharge from mine airway systems. As applied to a fan discharging to the atmosphere, it is termed an "evasee" discharge, the main purpose of which is to reduce the velocity at the point where abrupt expansion occurs. When a fan with an evasee is connected to discharge into an airway of the same size, abrupt expansion does not occur at this point, but at the actual discharge from the airway system.

For practical purposes, it is rarely economical to use a length that will make the discharge area more than four times the area at entrance to the diverging section, as the reduction in pressure loss for N_e ratios less than 0.25 is almost insignificant.

Abrupt Contraction.- Abrupt contraction followed by abrupt expansion is a common cause of pressure loss in mine airways and embraces all three common conditions of installation. This is not readily apparent unless it is realized that the areas actually occupied by the flow rather than airway areas are the determining factors. The common picture of abrupt contraction is that where a smaller section follows a larger section with abrupt transition in areas, as in Figure 11-C. Because the smaller area is the same as the opening, or orifice, the fact that abrupt expansion - from "vena contracta" to the smaller airway area - follows abrupt contraction is somewhat obscured. Here $N_e = 1$, and (38), (41), and (42) apply. Unrestricted entrance conditions present a quite similar form (figs. 9-A and 9-B), if the area preceding contraction is considered as expanded indefinitely. In addition to the special condition of $N_e = 1$ we also have the special condition that $N_c = 0$, so that (41) and (43) apply. In Figure 9-A we have the special condition of free contraction to an edge rather than the common condition of contraction against, or guided by, a surface. The average value of X_e, as given by numerous test data, is 0.90 and represents a Z value of 3.8. The usual value given for the flush-surface entrance condition (fig. 9-B) which corresponds to the standard entrance form for mine airways, is $X_e = 0.47$. The corresponding value of Z is 2.84, indicating that this value is not only for a very sharp-edged condition but probably also includes some friction pressure loss in the test installation. A better value for mine airways is $X_e = 0.34$, based on $Z = 2.5$ for a square edge. With a round, or beveled, edge with a radius, or bevel, approximately equal to the wall thickness of a lined mine airway, a Z value of 1.5 is probably sufficiently high, and X_e would be reduced to 0.05, a very low figure to be so easily obtained.

A restricted entrance, as in Figure 9-C, has only the one special condition that $N_c = 0$, from which it follows that the coefficient of contraction, c, by (43), is 0.633 for a square edge ($Z = 2.5$), 0.817 for a round edge ($Z = 1.5$), and 0.976 for a formed edge ($Z \doteq 1.05$).

Abrupt constrictions at discharge from a duct to the atmosphere (fig. 10-C) have only the special condition that $N_e = 0$, so that the special formulas (44) and (45) apply.

Flow through a small hole in the thin wall of a large chamber (fig. 10-E may be considered as a special condition of constricted discharge. Both N_c and N_e are so small that they can be considered to be 0, and formula (46), $X_o = Z$, applies. The values of X_o for square edge, round edge, and formed edge are therefore 2.5, 1.5, and 1.05, respectively, for mine airway applications. The values usually given range from about 2.7 to 2.8 and are for orifice plates with very sharp edges.

A constriction in an airway of uniform area (fig. 11-D) has only the special condition that $N_c = N_e$, so that no subscript is required for N, but the general formulas (34), (35), (36), and (38) apply. However, the more usual condition of actual application of a constriction in mine airways will involve unequal areas and we have the general condition of abrupt contraction followed by abrupt expansion (fig. 11-E) for which the general formulas liste above are required. For both cases, either tables of values, or graphic char are desirable to obviate computations.

Gradual Contraction.- Assuming that gradual contraction is followed by abrupt expansion from the "vena contracta" to the area following contraction the flow, the formulas and shock factors given for the preceding conditions o abrupt contraction would be affected only by the decrease in the normal value of Z, which may be determined roughly from Figure 8. For the special conditi of contraction at a uniform rate against a formed surface, as represented by the "standard orifice" in common use for air measurement and pictured for particular conditions of installation in Figures 9-B, 10-C, 10-E, and 11-D, there seems to be general agreement on coefficients of contraction that give a value of $Z = 1.05$; in other words, there is very little contraction of the flow against a well-formed surface. This form is particularly useful at the entrance to a pipe, where a slight flare reduces the pressure loss tremendousl and where a well-formed "bellmouth" has the insignificant shock factor of $X_e = 0.0006$ as against 0.90 for an unflared sharp edge.

The more common form of gradual contraction is that where a section of the airway converges in the direction of flow, and makes a gradual transition of areas. The common picture is that of a larger section converging on a uniform slope of sides to a smaller section, as in Figure 11-F. Here N_e is 1 and formulas (38) with Z derived from Figure 8 or a similar source, and (41) apply

In mine airways, a constriction that had been eased off on the approach side only might take the form shown in Figure 11-G, for which the general formulas are required, with Z values in (38) from Figure 8 or a similar source

A converging discharge from an airway (fig. 10-D) has the special condition that $N_e = 0$, so that the special formulas (44) and (45) apply, with c from (38) using Z from Figure 8.

A converging section used as the discharge from a chamber (fig. 10-F) or as entrance to an airway (Figure 9-D) actually combines abrupt contraction with gradual contraction. The latter can be separately determined, but N_e is indeterminate for the abrupt expansion following the abrupt contraction condition at entrance. Test data in Fan Engineering, pages 64-65, for the first condition mentioned, indicate that the loss accompanying the abrupt contractio at entrance is rapidly reduced as the included angle of the converging section is increased. Separate graphs are required for each condition of installation, but none are given here as these particular forms of installation of converging section have little practical application to mine airways.

Contraction Followed by Gradual Expansion.- Either abrupt or gradual contraction may be followed by gradual expansion, in which case the normal factors for abrupt expansion are multiplied by y, from Figure 7, according to (37). Few cases are met in practice except the combination of gradual contraction followed by gradual expansion. This combination allows of a large change of velocities and pressures with but a small pressure loss and is therefore extremely useful in fluid measurement methods based on pressure changes. The most common form is the standard "Venturi" (fig. 11-H), although equally good results may be obtained with the special "Venturi" (fig. 11-I) in which the converging section is replaced by the formed surface, for which Z may be taken as 1.05. Shock factors for the resulting shock loss, which primarily determines the cost of this form of air measurement for securing a continuous record, may be computed according to the general formulas (34) to (38) by the use of appropriate values of y from Figure 7 and, for the standard Venturi type, of Z from Figure 8, or similar sources.

Chart for Determining Shock Factors for Symmetrical Area Changes.- A graphic chart for the rapid determination of shock factors for the multitude of conditions of symmetrical contraction and expansion of the air stream that may be encountered in practice, is presented in Figure 12. It has four sections, marked A, B, C, and D, corresponding to the four possible steps in computations, all of which may or may not be required for a particular condition.

In A, the intersection of the proper value of Z with the curve for N_c determines the value of c from (38). In B, the intersection of the value of c with the curve for N_e determines the value of X_o from (35). Corresponding values of X_e and X_a are directly related to X_o through the velocity pressure-area ratio relations, $X_e = \frac{X_o}{N_e^2}$ and $X_a = \frac{X_o}{N_c^2}$; so in C the intersection of the proper value of X_o with the line for N_e determines the value of X_e, and, similarly, its intersection with the line for N_c determines the value of X_a. In D, the intersection of the proper value of X_o, X_e, or X_a for abrupt expansion with the line for the factor, y (from fig. 7), for the condition of gradual expansion, determines the corresponding value of X_o^1, X_e^1, or X_a^1 for gradual expansion. This section is not required, of course, for conditions of abrupt expansion; nor is section A required for conditions of abrupt expansion only, without preceding contraction, since we know that c = 1. In the latter case, $X_a = X_o$, and X_o for c = 1 is easily determined as the intercept of the N_e curve with the X_o scale in section B.

A continuous method of solving examples by the use of this chart is indicated on the chart by the solution of a particular example traced with arrows to show the directions of procedure. The example represents a condition of gradual expansion following abrupt contraction, with $Z = 2.5$, $N_c = 0.25$, $N_e = 0.35$, and $y = 0.3$. The solution shows that the shock factor corresponding

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to the area after expansion, X'_e, is 3.5, and that corresponding to the area before contraction, X'_a, is 6.9. Ordinarily we would not be interested in X'_o, but it could also be determined through section D if desired. The intermediate values of c, X_o, X_e, and X_a are shown to be 0.645, 1.44, 11.8, and 23.1, respectively.

Shock Factors for Mine Airway Enlargements, Constrictions and Obstructions

Obstructions in mine airways, whether along the walls as in the more norma type of contraction, or out in the air stream, as in the case of a mine car or cage, form more or less abrupt contractions and expansions in the air stream ar thus cause shock losses of the type under discussion. Some are symmetrical while others are not; contraction may occur on but one or more sides of rectangular openings, or only along the edges of obstructions in the airway; and an obstruction may be moving relative to the air flow and in the same or opposite direction. The few data that have been presented on symmetrical contractions and expansions, mainly on the few types involved in air measurement by pressure methods, do not begin to cover the field of shock losses in mine airways due to these causes and can serve only as a basis for very rough approximations until more data are obtained on the effect of unsymmetrical conditions of area changes on coefficients of contraction and shock loss.

Local Enlargements of Area and Dead Ends.- In mine airways there are many local enlargements of limited length in the area of the airway, and the change in area may be gradual or abrupt. Tests of a number of such conditions, such as shelter holes and breakthrough openings off coal-mine entries, dead-end stations off vertical metal-mine shafts, local widenings at side tracks in metal-mine drifts, and local increases in height in coal-mine entries at abandoned overcast locations, show that the increase over the normal for sections of airways containing such features is negligible. Such local enlargements usually occur on but one side of the airway and the abrupt unsymmetrical area changes are usually confined to dead ends of limited length in the direction of flow which the main current does not enter to any extent on account of its low angle of expansion. An eddy current will usually be found to be rotating in such dead ends, but the accompanying shock loss is negligible. Where the enlarged section is relatively long, the area gradations are usually less abrupt and the flow expands into the enlarged area. Shock losses occur due to gradual expansion and gradual contraction, but are counteracted by the decreased friction loss occasioned by the lower velocity of flow in the intermediate section, with the net result that the change in pressure loss over that of an equal length of normal cross-sectional area is usually negligible. The total pressure loss for sections including such enlargements may therefore be taken as equivalent to the friction loss for equal lengths of normal area.

Doorframes.- Doorframes at open doors on mine airways are a typical form of abrupt nonsymmetrical contraction, with contraction and expansion on but three sides of an off-center rectangle. Using the formulas for shock loss for symmetrical expansion as an approximation, computed Z values for two doors with square-timber frames, from Butte tests reported in Bulletin 261, pages 64-65, are 1.59 and 1.36. Since the exact edge conditions were not noted and the values of N_c and N_e were somewhat indeterminate on account of very variable areas adjacent to the doors, these values are not considered very reliable. That the figures are lower than the standard of 2.5 for a square edge is no doubt partly due to gradual contraction on one side caused by the open door and partly to special edge conditions, which apparently more than offset the increase in shock losses between symmetrical and 3-sided expansion. Until better-substantiated methods are available, it is recommended that the formulas for symmetrical expansion be used with $Z = 2.5$ for a square-timber frame only, and $Z = 2.0$ for the same frame with the door open.

Regulators.- A common device used in the distribution of air currents in mines is a small opening in a stopping with the size regulated, usually by means of a sliding shutter, to cause a certain increased pressure loss on one flow circuit in order to improve the flow on other circuits. It is simply a device for causing a desired loss of pressure, and amounts to installing a square-edged orifice (fig. 11-D) in the airway. A value of 2.5 for Z is probably sufficiently high for a symmetrically placed regulator opening, but the value of Z that should be used for different degrees of unsymmetrical placing, particularly where the regulator is placed in a stopping that is parallel to the main flow, as at a split or junction, is entirely unknown at present.

Lagging Across Mine Airways.- The bureau's Butte test work gives values (Bull. 261, p. 54) of velocity pressure losses for lagging laid across the center of vertical shaft compartments, from which a Z factor of 5.2 has been computed, as for symmetrical expansion as before, for this type of contraction as caused by an obstruction to the air flow. For a center post of roughly squared timber in a coal-mine entry, the bureau's Experimental mine test work (Bull. 285, p. 51) gives data from which a Z value of 5.3 has been computed, which is in substantial agreement with the value for lagging. In contraction caused by obstructions of this type, contraction takes place only along the perimeter of the obstruction and not along the walls, and the high values of Z indicate that the degree of contraction, or the decrease in area from the edge to the "vena contracta," is much larger than for contraction across the whole perimeter at the contracted area. This effect is entirely rational, since we know that a greater width of the air flow is deflected for the same value of N_c, or ratio of contraction in area of the airway. For similar narrow obstructions, not centered either horizontally or vertically in the air stream, the values of Z would probably be less, since the velocities of flow are always a maximum at or near the center of the airway.

Mine Cars.- A mine car, or trip of cars, is a similar type of contraction of the air stream, but in this case the obstruction is so long that three pressure losses are involved. First, there is abrupt contraction, similar to the preceding case, except that the expansion following contraction takes place in the constricted area, somewhat similar to Figure 11-C, which is the same approximately as that of the orifice. Second, there is the increase in friction pressure loss due to flow for a certain length of airway in the constricted section rather than in the full area of airway. And third, there is abrupt expansion from the constricted area to the full area of the airway, somewhat similar to Figure 11-A.

Calculation of the bureau's Experimental mine test data for pressure losses due to mine cars in coal-mine entry (Bull. 285, pp. 52-66), which are confirmed by a few tests in Butte metal mines, reported in Bulletin 261, page 145, gives a Z value, derived from the formulas for symmetrical area changes, for the front of a car (or cage) of about 5.35, which is quite similar to those calculated for lagging and center post, although an approximate value of 5 for all similar conditions is probably as close as the accuracy of the test data and the uncertainty of the method of computation justifies at present. This indicates that the Z values for obstructions are about twice those for wall contraction for similar edge conditions. The shock factors for obstructions given in Table 1 are based on this tentative assumption.

The increased friction loss due to increased velocities through the constricted area is rarely large enough to justify precise calculations and for ordinary purposes can be taken as equivalent to $\frac{2 - N}{N^2}$ times the normal loss for the same length of unobstructed airway, where N is the ratio of constricted area to normal area. The actual ratio of losses depends on the relative shapes of airway and obstruction and can, of course, be calculated exactly for the particular conditions. The expression given serves for computing the loss with an accuracy within about 5 per cent for average coal and metal mine airway conditions and is thus sufficiently precise.

Shielding Effect of Obstructions.- The bureau's experimental mine tests on cars also bring out an effect of closely-spaced obstructions to flow which is commonly referred to as the "shielding effect." When the obstructions to flow are so closely spaced that the flow does not have a sufficient distance downstream in which to expand fully before encountering another obstruction, the expansion is not carried out to the fullest extent possible and the shock loss is thereby diminished to that corresponding to a higher value of N_e than the actual areas would indicate. Tests on coal-mine cars in a coal-mine entry (Bull. 285, pp. 58-59) showed that the cars had to be spaced about 30 feet center to center (about 25 feet clear distance between cars) before the pressure loss due to a group of cars was equivalent to that for one car multiplied by the number of cars. With the cars in a closely-coupled train, the normal condition, there is but one front shock loss and one rear shock loss, and the intermediate cars contribute only the increased friction loss in the constricted airway proportional to the total length they occupy coupled together.

Moving Obstructions.- Although no test data appear to be available for cars, skips, and cages in motion, it is entirely possible that the pressure losses can be calculated approximately from the data on hand, provided that effective velocities - velocity of air movement plus or minus the velocity of movement of the obstruction - are used instead of actual velocities in computing the shock and friction losses involved. However, a body in movement in an airway acts like a loose piston and generates pressure which may, or may not, be opposed to the normal direction of movement of the air current. Data on such pressure generation are undoubtedly available from aeronautical research, but no method of applying them to airway conditions has been developed, to the author's knowledge.

Large volume circulations are often temporarily reversed by rapid movement of skips and cages in shafts and trains of cars on horizontal airways, where the moving object makes a rather close fit with the airway or where the pressure inducing the circulation is small, as in natural-draft ventilation. In an open-timbered shaft the movement of skips or cages operating in balance has but a minor effect on the air flow, since opposing pressures are generated and there is always plenty of clearance for the air flow in adjoining compartments. Where the air flow is in separately lined compartments with small clearance, the piston effect is large but is usually limited considerably by the provision of openings between compartments at frequent intervals. As a rule, these are provided to facilitate shaft repairs but serve the further purpose of limiting the piston effect of cage and skip travel and thus reduce interference with the normal distribution.

Calculations based on observations of air velocities and traffic counts by bureau engineers in 1924 in the parallel Liberty vehicular tunnels in Pittsburgh, before the installation of mechanical ventilation and with ventilation entirely by natural draft and car-generated pressures, show net pressures generated per automobile of 0.005 to 0.02 inch of water per car for car speeds averaging about 30 to 35 miles per hour (2,640 to 3,080 feet per minute) and with an average cross section of car estimated to be about 23 square feet in tunnels of 468 square feet sectional area. The lower net pressures per car obtained at the higher velocities of flow, which ranged up to 1,000 feet per minute in the direction of car travel, and the higher pressures per car obtained with the lower velocities. As the velocity of flow increased, the difference in velocities between car travel and air travel decreased and there was also more shielding effect of one car on a closely following car, thus decreasing the net pressure generated per car. A considerable amount of test work will apparently be required before we will be able to gage even approximately the effects of moving obstructions in airways.

Shock Losses at Splits and Junctions

Where part of the air current leaves or enters the main current, we have splits or junctions which involve shock losses due to both changes in direction and area changes. The few test data available indicate that, for splits or leaving currents, the losses are comparable to bend losses except that the velocity pressure of the partial current, or current in the split, should be used. Where air currents enter the main stream, however, both reasoning and test data indicate that the normal deflection shock losses for the entering stream are increased by its interference with the air stream of the main current. Exact quantitative data are lacking, but since the effects are known to be of considerable magnitude, it seems prudent to use X factors for normal conditions, based on the velocity pressure of the entering stream, multiplied by at least 1.5, or an allowance of 50 per cent.

It is evident that the shock losses at splits and junctions are largely determined by the proportional divisions of the total quantity of flow, which are dependent on the total of both friction and shock losses in the branch circuits as well as the shock losses at entrance and departure in each. Problems of distribution are therefore difficult. Approximate solutions require a reasonably close estimate of the proportional divisions of the flow, and accurate solutions are only arrived at through a process of trial and error.

Practically all splits and junctions in mine airways present the types of irregular conditions, such as nonuniform areas at bends and unsymmetrical area changes, for which we have no strictly rational methods of computation; and while we may have a few directly-determined shock factors for special combinations, we will be practically without data for these important types of pressure losses in mine airways until rational methods of computation have been developed.

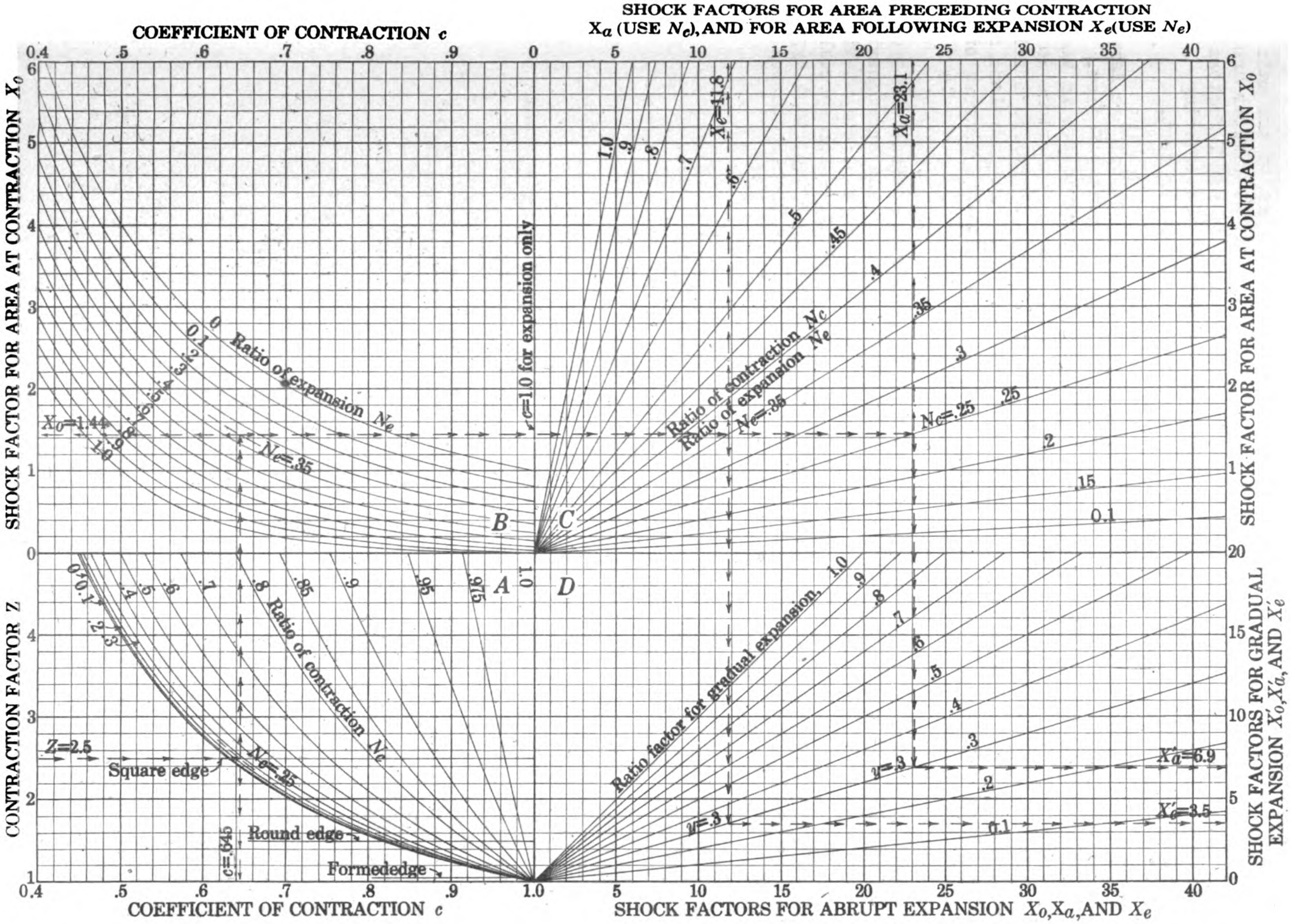

Figure 12.- Chart for determining shock factors, or shock pressure losses in terms of equivalent velocity pressures, for symmetrical changes in area of airways

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